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Enantioselective cycloaddition of carbonyl ylides with arylallenes using Rh_2(*S*-TCPTTL)$_4$†

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The first catalytic asymmetric carbonyl ylide cycloaddition with arylallenes is described. With dirhodium(II) tetrakis[*N*-tetrachlorophthaloyl-(*S*)-*tert*-leucinate], Rh_2(*S*-TCPTTL)$_4$, the cycloaddition of carbonyl ylides derived from diazoketoesters with arylallenes proceeded in a fully chemo- and regioselective manner to give highly functionalized 8-oxabicyclo[3.2.1]octanes with up to 99% ee and perfect *exo* diastereoselectivity.

Introduction

The dirhodium(II) complex-catalyzed tandem cyclic carbonyl ylide formation 1,3-dipolar cycloaddition is one of the most powerful methods for rapid assembly of complex oxapolycyclic systems.[1] The exceptional power of the carbonyl ylide cycloaddition strategy has recently been demonstrated by an increasing number of syntheses of diverse natural products.[2–4] Over the past 15 years, an enantioselective version of this sequence catalyzed by chiral dirhodium(II) complexes has also been realized in some selected reactions,[5,6] in which a prime requirement for asymmetric induction is the use of chiral dirhodium(II) catalyst-associated carbonyl ylide intermediates in the cycloaddition step because catalyst-free carbonyl ylides are achiral. Recently, we reported catalytic enantioselective intermolecular cycloadditions of carbonyl ylides derived from diazoketoesters with terminal aryl alkynes and alkenes, and *N*-methylindoles,[7] in which Rh_2(*S*-TCPTTL)$_4$ (**1c**)[7,8] (Fig. 1), the chlorinated analogue of Rh_2(*S*-PTTL)$_4$ (**1a**), proved to be the catalyst of choice for achieving high levels of asymmetric induction (up to 99% ee).[9] To further advance this catalytic process with respect to a dipolarophile, we addressed the cycloaddition of carbonyl ylides with allenes, which has been less studied.[10–12]

Allenes are interesting dipolarophiles due to the presence of cumulated C=C bonds. In fact, both C=C bonds of allenes take suitable positions for dipolar attack, which can proceed with two opposite orientations.[13–16] Hence, as well as enantiocontrol, control of chemo-, regio-, and diastereoselectivity is a major challenge in enantioselective carbonyl ylide cycloadditions with allene dipolarophiles. While only one example of asymmetric induction (up to 45% ee) in cycloaddition of carbonyl ylide derived from diazodione with allene was demonstrated by Hodgson *et al.* using Rh_2(*S*-DOSP)$_4$ (**2**)[17] as a chiral catalyst,[11] at the outset of our studies, there were no reported examples of this type of cycloaddition with substituted allenes, even in a racemic reaction.[18] Herein, we report the first example of enantioselective cycloaddition of carbonyl ylides with arylallenes, in which catalysis with Rh_2(*S*-TCPTTL)$_4$ proceeds in a fully chemo- and regioselective manner to give highly functionalized 8-oxabicyclo[3.2.1]octane derivatives, potentially useful chiral building blocks or intermediates in organic synthesis,[19,20] in high yields with high levels of enantioselectivity (up to 99% ee) and perfect *exo* diastereoselectivity.

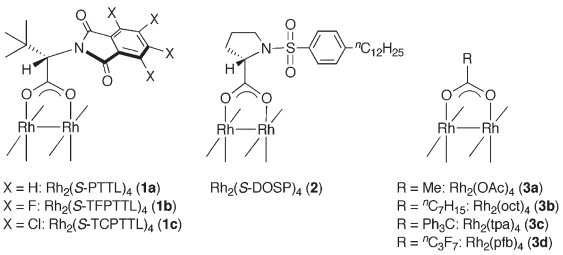

Fig. 1 Dirhodium(II) complexes.

Results and discussion

On the basis of our previous work,[7a] we initially explored the cycloaddition of a cyclic carbonyl ylide derived from 2-diazo-3,6-diketoester **4a** with 2 equiv. of phenylallene (**5a**)[21] in the

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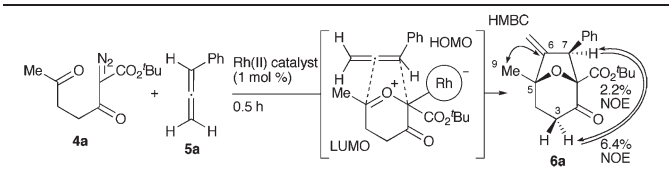
†Electronic supplementary information (ESI) available: Copies of ^{1}H and ^{13}C NMR spectra of all new compounds and HPLC analysis. X-ray data (CIF) for **6d** is also provided. CCDC 934102. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c3ob41236a

Table 1 Enantioselective intermolecular cycloaddition of 2-diazo-3,6-diketoester **4a** with phenylallene (**5a**) catalyzed by **1a–c**[a]



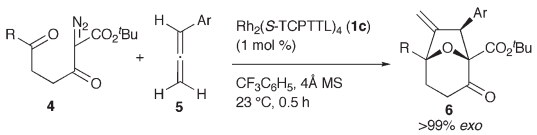
Entry	Rh(II) catalyst	Temp. (°C)	Solvent	Additive	Yield[b] (%)	ee[c] (%)
1	**1c**	23	$CF_3C_6H_5$	—	63	99
2	**1c**	0	$CF_3C_6H_5$	—	61	99
3	**1c**	60	$CF_3C_6H_5$	—	24	96
4	**1c**	23	Toluene	—	45	99
5	**1c**	23	Benzene	—	34	90
6	**1c**	23	CH_2Cl_2	—	Trace[d]	—
7	**1c**	23	$CF_3C_6H_5$	4 Å MS	82	99
8	**1a**	23	$CF_3C_6H_5$	4 Å MS	Trace[d]	—
9	**1b**	23	$CF_3C_6H_5$	4 Å MS	20	96

[a] All reactions were carried out as follows: Rh(II) catalyst (1 mol%) was added to a stirred solution of **4a** (48 mg, 0.2 mmol) and **5a** (2 equiv.) in the indicated solvent (2 mL) at the indicated temperature. [b] Yields of isolated product **6a**. [c] Determined by HPLC analysis using a Daicel Chiralpak IC. [d] Detected in a complex mixture of products.

presence of 1 mol% of Rh_2(*S*-TCPTTL)$_4$ (**1c**). The reaction in α,α,α-trifluorotoluene proceeded smoothly at room temperature to give cycloadduct **6a** as the sole product in 63% yield (Table 1, entry 1). This result demonstrated that the reaction proceeds in a fully regioselective fashion and undergoes cycloaddition across the phenyl substituted C=C bond (*vide infra*). The *exo*-stereochemistry of **6a** was established by a ^{1}H-NOE between H-7 and H-3, while ^{1}H–^{13}C HMBC correlation between H-9 and C-6 confirmed the position of the exocyclic methylene group. The enantioselectivity of this reaction was determined to be 99% ee by HPLC analysis using a Daicel Chiralpak IC column. A series of experiments were then carried out in an attempt to achieve a high-yielding formation of **6a**. Lowering the reaction temperature to 0 °C led to a slight decrease in the product yield, while the same enantioselectivity was observed (61% yield, 99% ee, entry 2). The reaction at 60 °C resulted in a sharp drop in the product yield with a slight decrease in enantioselectivity (24% yield, 96% ee, entry 3). Experiments with other solvents such as toluene and benzene exhibited high levels of enantioselectivity comparable to that found with α,α,α-trifluorotoluene, but product yields were markedly reduced (entries 4 and 5). CH_2Cl_2 was found to be the least effective, giving only a trace amount of **6a** (entry 6). To our delight, addition of powdered 4 Å MS greatly improved the product yield without compromising the enantioselectivity or *exo* diastereoselectivity (82%, 99% ee, entry 7).[22] Using α,α,α-trifluorotoluene as a solvent and 4 Å MS as an additive, we next evaluated the performance of Rh_2(*S*-PTTL)$_4$ (**1a**)[23,24] and Rh_2(*S*-TFPTTL)$_4$ (**1b**).[25] Unlike the previous work,[7] catalysis with Rh_2(*S*-PTTL)$_4$ led to only trace amounts of **6a** (entry 8), while the use of Rh_2(*S*-TFPTTL)$_4$, the fluorinated analogue of **1a**, provided a similar level of enantioselectivity but a significantly lower yield of **6a** (entry 9). We were also surprised to find that achiral catalysts such as $Rh_2(OAc)_4$ (**3a**), $Rh_2(oct)_4$ (**3b**), $Rh_2(tpa)_4$ (**3c**), and $Rh_2(pfb)_4$ (**3d**) gave a complex mixture of products with no signs of cycloadduct **6a**,[26] although $Rh_2(OAc)_4$ worked well in the Hodgson[11] and Harned[18] reaction systems. Clearly, the advantage of Rh_2(*S*-TCPTTL)$_4$ extends beyond stereocontrol in this system. These results indicate that the presence of tetrachlorophthalimido groups in the bridging ligands of **1c** is crucial for the efficiency of the cycloaddition. It seems likely that Rh_2(*S*-TCPTTL)$_4$ with a powerful electron-withdrawing effect of the chlorine substituent generates an even longer-lived catalyst-bound carbonyl ylide than does any other dirhodium(II) catalyst to favor the cycloaddition with phenylallene, whereas the catalyst-free ylide is too short-lived to undergo such a cycloaddition.[27]

With the optimized conditions in hand, we then explored the reaction of **4a** with a range of arylallenes (Table 2). Apart from complete chemo- and regioselectivity, perfect *exo* diastereoselectivity and high enantioselectivity were consistently observed with arylallenes bearing methyl, methoxy, bromo, and trifluoromethyl groups at the *para* position on the benzene ring (92–97% ee, entries 2–5). The absolute configuration of **6d** was determined to be (1*R*,5*R*,7*R*) by single-crystal X-ray analysis (see the ESI†), and the stereochemistry of other cycloadducts was assigned by analogy. High levels of asymmetric induction were maintained with *m*- or *o*-methylphenylallenes as well as with

Table 2 Enantioselective intermolecular cycloaddition of diazoketoesters **4** with arylallenes **5** catalyzed by Rh_2(*S*-TCPTTL)$_4$ (**1c**)[a]



Entry	Product		Diazoketoester R		Dipolarophile Ar		
						Yield[b] (%)	ee[c] (%)
1	**4a**	Me	**5a**	C_6H_5	**6a**	82	99
2	**4a**	Me	**5b**	4-MeC_6H_5	**6b**	77	92
3	**4a**	Me	**5c**	4-MeOC_6H_5	**6c**	89	97
4	**4a**	Me	**5d**	4-BrC_6H_5	**6d**	71	96
5	**4a**	Me	**5e**	4-$CF_3C_6H_5$	**6e**	72	97
6	**4a**	Me	**5f**	3-MeC_6H_5	**6f**	65	92
7	**4a**	Me	**5g**	2-MeC_6H_5	**6g**	82	99
8	**4a**	Me	**5h**	3-MeOC_6H_5	**6h**	65	98
9	**4a**	Me	**5i**	2-MeOC_6H_5	**6i**	63	83
10	**4b**	H	**5a**	C_6H_5	**6j**	80	96
11	**4b**	H	**5c**	4-MeOC_6H_5	**6k**	75	96
12	**4b**	H	**5d**	4-BrC_6H_5	**6l**	73	92
13	**4b**	H	**5e**	4-$CF_3C_6H_5$	**6m**	68	98
14	**4b**	H	**5g**	2-MeC_6H_5	**6n**	76	99
15	**4c**	C_6H_5	**5a**	C_6H_5	**6o**	96	97
16	**4c**	C_6H_5	**5c**	4-MeOC_6H_5	**6p**	94	94
17	**4c**	C_6H_5	**5e**	4-$CF_3C_6H_5$	**6q**	88	99
18	**4c**	C_6H_5	**5g**	2-MeC_6H_5	**6r**	98	99

[a] All reactions were performed on a 0.2 mmol scale with 2 equiv. of **5**. [b] Yields of isolated product **6**. [c] Determined by HPLC analysis.

m-methoxyphenylallene (92–99% ee, entries 6–8), while only modest enantioselectivity was observed with *o*-methoxyphenylallene (83% ee, entry 9). We finally investigated the reaction of diazoketoesters **4b,c**[7,9] bearing substituents other than a methyl group at the C-5 position. The cycloaddition of formyl-derived or phenyl-substituted carbonyl ylides with arylallenes proceeded also in a completely chemo-, and regioselective manner to give the corresponding cycloadducts **6j–r** in good to high yields with high to excellent enantioselectivities (92–99% ee, entries 10–18).

From frontier molecular orbital (FMO) analysis for these reactions in the absence of a catalyst (see the ESI†), the chemo- and regiocontrol observed can be readily rationalized in terms of maximum overlap of the LUMO of carbonyl ylides derived from **4a–c** and the HOMO of arylallene dipolarophiles **5a–d** and **5f–i** (Table 2, entries 1–4, 6–12, 14–16 and 18).[7,28] FMO analysis, however, fails to explain the same regiochemistry encountered with a strongly electron-deficient *p*-(trifluoromethyl)phenylallene (**5e**) (Table 2, entries 5, 13 and 17). The calculations suggest that the favored cycloadduct should be the result of interaction between the HOMO of carbonyl ylide derived from **4a** and the LUMO of **5e** (*i.e.*, ΔE = 7.76 eV) rather than the dipole LUMO–dipolarophile HOMO interaction (*i.e.*, ΔE = 8.37 eV). One possible explanation for the exclusive formation of **6e**, **6m** and **6q** is that the association of Rh_2(*S*-TCPTTL)$_4$ with the carbonyl ylide as shown in Table 1 leads to significant lowering of the LUMO energy level compared with the catalyst-free carbonyl ylide and facilitates the interaction between its LUMO and the HOMO of **5e**, which predicts the regiochemistry exactly as observed.

Conclusions

In summary, we have developed a catalytic enantioselective cycloaddition of carbonyl ylides derived from diazoketoesters with a broad range of arylallenes, in which the unique ability of Rh_2(*S*-TCPTTL)$_4$ has been demonstrated. The LUMO-controlled carbonyl ylide cycloaddition reaction (even with the electron-deficient *p*-(trifluoromethyl)phenylallene) in the presence of 4 Å MS proceeded in a fully chemo- and regioselective fashion to give 7-aryl-6-methylene-8-oxabicyclo[3.2.1]octane derivatives otherwise difficult to construct in high yields with exceptionally high levels of enantioselectivity (up to 99% ee) and perfect *exo* diastereoselectivity. Notably, this is the first example of the use of arylallenes as dipolarophiles in enantioselective cycloaddition reactions with any type of 1,3-dipoles.[16] Applications of this method to catalytic asymmetric synthesis of biologically active natural products as well as mechanistic and stereochemical studies are currently in progress.

Experimental

General methods

IR spectra were recorded using a JASCO FT/IR-5300 spectrometer and absorbance bands are reported in wavenumber (cm^{-1}). ^1H NMR spectra were recorded using JEOL ECS-400 (400 MHz) spectrometer. Chemical shifts are reported relative to internal standard (tetramethylsilane; δ_H 0.00). Data are presented as follows: chemical shift (δ, ppm), multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet, br = broad), coupling constant and integration. ^{13}C NMR spectra were recorded using a JEOL ECS-400 (100 MHz) spectrometer. Chemical shifts are reported relative to the internal standard ($CDCl_3$; δ 77.00). Optical rotations were measured using a JASCO P-1030 digital polarimeter at the sodium D line (589 nm). ESI-MS spectra were obtained using a Thermo Scientific Exactive spectrometer. Column chromatography was carried out using Kanto silica gel 60 N (63-210 mesh) or Wakogel® C-200 (75–200 μm). Analytical thin layer chromatography (TLC) was carried out using Merck Kieselgel 60 F_{254} plates with visualization by ultraviolet, anisaldehyde stain solution or phosphomolybdic acid stain solution followed by heating. Analytical high performance liquid chromatography (HPLC) was performed using a JASCO PU-1580 intelligent HPLC pump with a JASCO UV-1575 intelligent UV/VIS detector. Detection was performed at 206 nm, 226 nm and 254 nm. Chiralpak IC or Chiralpak AD-H columns (0.46 cm × 25 cm) from Daicel were used. Retention times (t_R) and the peak ratio were determined using a JASCO-ChromNAV analysis system.

All non-aqueous reactions were carried out in flame-dried glassware under an argon atmosphere. Reagents and solvents were purified by standard means. $CF_3C_6H_5$ was distilled from CaH_2. 4 Å MS-powder from Fluka was used after drying (100 °C, 1 mmHg, 12 h). Arylallenes **5a–i** were prepared according to literature procedures.[29] Chiral dirhodium(II) carboxylates **1a–c** were prepared according to our previous reports.[30]

Typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition: (1*R,5*R**,7*R**)-1-*tert*-butoxycarbonyl-5-methyl-6-methylene-7-phenyl-8-oxabicyclo[3.2.1]octan-2-one (6a) (Table 1, entry 7).** Rh_2(*S*-TCPTTL)$_4$ (**1c**) (3.95 mg, 0.0020 mmol, 1 mol%) was added to a stirred solution of 4 Å MS-powder (50 mg), α-diazo-β-ketoester **4a**[5d] (48.0 mg, 0.20 mmol) and phenylallene (**5a**)[29a] (46.4 mg, 0.40 mmol) in $CF_3C_6H_5$ (2.0 mL) at 23 °C. After stirring for 30 minutes, the reaction mixture was filtered through Celite. The filtrate was concentrated *in vacuo* and the residue was purified using column chromatography (silica gel, 15 g, 8 : 2 hexane–EtOAc) to provide cycloadduct **6a** (54 mg, 82%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.50; M.p. 140–142 °C (99% ee); $[\alpha]_D^{24}$ = +95.9 (*c* 1.0, $CHCl_3$); IR (KBr): ν = 2978, 2933, 1738, 1367, 1314, 1164, 1078 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.06 (s, 9H, $C(CH_3)_3$), 1.67 (s, 3H, CH_3), 2.01–2.06 (m, 1H, CH_2), 2.33–2.41 (m, 1H, CH_2), 2.50–2.56 (m, 1H, CH_2), 2.64–2.70 (m, 1H, CH_2), 4.00 (d, *J* = 1.6 Hz, 1H, CH), 4.98 (d, *J* = 1.6 Hz, 1H, C10–H), 5.15 (d, *J* = 1.6 Hz, 1H, C10–H), 7.21–7.29 (m, 5H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.5 (CH_3), 27.2 ($C(CH_3)_3$), 34.4 (CH_2), 39.8 (CH_2), 56.3 (CH), 82.1 (C), 83.6 (C), 92.0 (C), 109.2 (CH_2), 127.0 (CH), 128.2 (CH), 128.5 (C), 142.4 (C), 157.0 (C), 164.8 (C), 200.7 (C); HRMS (ESI) *m*/*z* calcd for $C_{20}H_{24}O_4Na$ $[M + Na]^+$ 351.1566, found 351.1567. Anal. Calcd for $C_{20}H_{24}O_4$: C, 73.15; H, 7.37. Found: C, 72.97; H, 7.32.

The enantiomeric excess of **6a** was determined to be 99% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 18.9 min; t_R (major) = 20.4 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-5-methyl-6-methylene-7-(4-methylphenyl)-8-oxabicyclo[3.2.1]octan-2-one (6b).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6b** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 4-methylphenylallene (**5b**)[29a] (52.0 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to afford **6b** (53.0 mg, 77%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.65; M.p. 159–161 °C (92% ee); $[\alpha]_D^{24}$ = +108.2 (*c* 1.3, $CHCl_3$); IR (KBr): ν = 2981, 2925, 1730, 1513, 1366, 1313, 1163, 1079 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.01 (s, 9H, $C(CH_3)_3$), 1.66 (s, 3H, CH_3), 1.99–2.05 (m, 1H, CH_2), 2.30 (s, 3H, CH_3), 2.32–2.39 (m, 1H, CH_2), 2.48–2.55 (m, 1H, CH_2), 2.63–2.72 (m, 1H, CH_2), 3.97 (t, *J* = 2.0 Hz, 1H, CH), 4.97 (d, *J* = 2.0 Hz, 1H, C10–H), 5.13 (d, *J* = 2.0 Hz, 1H, C10–H), 7.07 (d, *J* = 8.3 Hz, 2H, Ar), 7.13 (d, *J* = 8.3 Hz, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.0 (CH_3), 23.5 (CH_3), 27.2 ($C(CH_3)_3$), 34.4 (CH_2), 39.8 (CH_2), 56.0 (CH), 82.0 (C), 83.5 (C), 92.0 (C), 108.9 (CH_2), 128.0 (CH), 129.0 (CH), 136.6 (C), 139.4 (C), 157.1 (C), 164.8 (C), 200.7 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{26}O_4Na$ $[M + Na]^+$ 365.1723, found: 365.1724. Anal. Calcd for $C_{21}H_{26}O_4$: C, 73.66; H, 7.65. Found: C, 73.80; H, 7.61.

The enantiomeric excess of **6b** was determined to be 92% by HPLC analysis using a Daicel Chiralpak IC column (3 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 10.2 min; t_R (major) = 11.7 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(4-methoxyphenyl)-5-methyl-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6c).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6c** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 4-methoxyphenylallene (**5c**)[29a] (58.4 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to give **6c** (63.7 mg, 89%) as a colorless solid; R_f (7 : 3 hexane–EtOAc) = 0.50; M.p. 161–161.5 °C (97% ee); $[\alpha]_D^{24}$ = +184.0 (*c* 1.3 $CHCl_3$); IR (KBr): ν = 2979, 1743, 1728, 1510, 1241, 1077 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.10 (s, 9H, $C(CH_3)_3$), 1.66 (s, 3H, CH_3), 1.99–2.05 (m, 1H, CH_2), 2.33–2.40 (m, 1H, CH_2), 2.49–2.55 (m, 1H, CH_2), 2.62–2.69 (m, 1H, CH_2), 3.77 (s, 3H, CH_3), 3.98 (s, 1H, CH), 4.96 (d, *J* = 1.6 Hz, 1H, C10–H), 5.12 (d, *J* = 1.6 Hz, 1H, C10–H), 6.80 (d, *J* = 8.3 Hz, 2H, Ar), 7.15 (d, *J* = 8.3 Hz, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.6 (CH_3), 27.4 ($C(CH_3)_3$), 34.4 (CH_2), 39.8 (CH_2), 55.3 (OCH_3), 55.7 (CH), 82.1 (C), 83.5 (C), 92.1 (C), 108.9 (CH_2), 113.8 (CH), 129.3 (CH), 134.7 (C), 157.3 (C), 158.7 (C), 164.8 (C), 200.7 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{26}O_5Na$ $[M + Na]^+$ 381.1672, found 381.1673. Anal. Calcd for $C_{21}H_{26}O_5$: C, 70.37; H, 7.31. Found: C, 70.11; H, 7.35.

The enantiomeric excess of **6c** was determined to be 97% by HPLC analysis using a Daicel Chiralpak IC column (3 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 11.4 min; t_R (major) = 14.4 min.

(1*R*,5*R*,7*R*)-7-(4-Bromophenyl)-1-*tert*-butoxycarbonyl-5-methyl-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6d). According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6d** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 4-bromophenylallene (**5d**)[29b] (78.0 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to provide **6d** (57.8 mg, 71%) as a pale yellow solid; R_f (7 : 3 hexane–EtOAc) = 0.50; M.p. 158–159 °C (96% ee); $[\alpha]_D^{22}$ = +88.7 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 2982, 2921, 1735, 1486, 1368, 1314, 1160, 1076, 897, 838 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.10 (s, 9H, $C(CH_3)_3$), 1.66 (s, 3H, CH_3), 2.00–2.05 (m, 1H, CH_2), 2.33–2.40 (m, 2H, CH_2), 2.50–2.56 (m, 1H, CH_2), 2.62–2.71 (m, 1H, CH_2), 3.98 (s, 1H, CH), 4.97 (d, *J* = 2.0 Hz, 1H, C10–H), 5.16 (d, *J* = 2.0 Hz, 1H, C10–H), 7.13 (d, *J* = 7.9 Hz, 2H, Ar), 7.40 (d, *J* = 7.9 Hz, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.6 (CH_3), 27.3 ($C(CH_3)_3$), 34.3 (CH_2), 39.6 (CH_2), 55.6 (CH), 82.4 (C), 83.6 (C), 91.8 (C), 109.6 (CH_2), 120.9 (C), 129.8 (CH), 131.5 (CH), 141.5 (C), 156.5 (C), 164.6 (C), 200.3 (C); HRMS (ESI) *m*/*z* calcd for $C_{20}H_{23}BrO_4Na$ $[M + Na]^+$ 429.0671, found 429.0672. Anal. Calcd for $C_{20}H_{23}BrO_4$: C, 58.98; H, 5.69; Br, 19.62. Found: C, 58.70; H, 5.66; Br, 19.23.

The enantiomeric excess of **6d** was determined to be 96% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 14.7 min for (1*S*,5*S*,7*S*)-enantiomer; t_R (major) = 17.5 min for (1*R*,5*R*,7*R*)-enantiomer.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(4-(trifluoromethyl)-phenyl)-5-methyl-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6e).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6e** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 4-(trifluoromethyl)phenylallene (**5e**)[29c] (73.7 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to afford **6e** (57.0 mg, 72%) as a pale yellow solid; R_f (7 : 3 hexane–EtOAc) = 0.45; M.p. 161–161.5 °C (97% ee); $[\alpha]_D^{22}$ = +55.0 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 3001, 2984, 2936, 1730, 1618, 1421, 1370, 1332, 1163, 1120, 1081, 1021, 902, 825 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.06 (s, 9H, $C(CH_3)_3$), 1.68 (s, 3H, CH_3), 2.02–2.08 (m, 1H, CH_2), 2.35–2.43 (m, 1H, CH_2), 2.53–2.59 (m, 1H, CH_2), 2.63–2.69 (m, 1H, CH_2), 4.08 (s, 1H, CH), 4.98 (s, 1H, C10–H), 5.20 (s, 1H, C10–H), 7.38 (d, *J* = 7.5 Hz, 2H, Ar), 7.54 (d, *J* = 7.5 Hz, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.6 (CH_3), 27.2 ($C(CH_3)_3$), 34.3 (CH_2), 39.6 (CH_2), 55.9 (CH), 82.6 (C), 83.7 (C), 91.8 (C), 109.9 (CH_2), 125.4 (CH), 127.8 (C), 128.4 (CH), 129.2 (C), 146.4 (C), 156.3 (C), 164.5 (C), 200.1 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{23}F_3O_4Na$ $[M + Na]^+$ 419.1549, found 419.1548. Anal. Calcd for $C_{21}H_{23}F_3O_4$: C, 63.63; H, 5.85; F, 14.38. Found: C, 63.52; H, 5.81; F, 14.5.

The *exo*-stereochemistry of **6e** was established by using a ^1H-NOE between H-7 and H-3, while ^1H–^{13}C HMBC correlation between H-9 and C-6 confirmed the position of the exocyclic methylene group (see the ESI†).

The enantiomeric excess of **6e** was determined to be 97% by HPLC analysis using a Daicel Chiralpak IC column

(19 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 15.7 min; t_R (major) = 19.5 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-5-methyl-6-methylene-7-(3-methylphenyl)-8-oxabicyclo[3.2.1]octan-2-one (6f).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6f** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 3-methylphenylallene (**5f**)[29b] (52.0 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to give **6f** (44.5 mg, 65%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.5; M.p. 138–139 °C (92% ee); $[\alpha]_D^{20}$ = +121.8 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 2981, 2933, 1742, 1728, 1313, 1166, 1081 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.06 (s, 9H, $C(CH_3)_3$), 1.67 (s, 3H, CH_3), 2.00–2.08 (m, 1H, CH_2), 2.31 (s, 3H, CH_3), 2.34–2.40 (m, 1H, CH_2), 2.49–2.55 (m, 1H, CH_2), 2.63–2.72 (m, 1H, CH_2), 3.96 (t, *J* = 2.0 Hz, 1H, CH), 4.98 (d, *J* = 2.0 Hz, 1H, C10–H), 5.14 (d, *J* = 2.0 Hz, 1H, C10–H), 7.02–7.04 (m, 3H, Ar), 7.13–7.17 (m, 1H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.3 (CH_3), 23.5 (CH_3), 27.2 ($C(CH_3)_3$), 34.4 (CH_2), 39.8 (CH_2), 56.3 (CH), 82.0 (C), 83.5 (C), 92.0 (C), 109.0 (CH_2), 125.1 (CH), 127.7 (CH), 128.4 (CH), 128.9 (CH), 137.9 (C), 142.3 (C), 156.9 (C), 164.7 (C), 200.7 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{26}O_4Na$ $[M + Na]^+$ 365.1723, found 365.1724. Anal. Calcd for $C_{21}H_{26}O_4$: C, 73.66; H, 7.65. Found: C, 73.42; H, 7.63.

The enantiomeric excess of **6f** was determined to be 92% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 20.9 min; t_R (major) = 24.1 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-5-methyl-6-methylene-7-(2-methylphenyl)-8-oxabicyclo[3.2.1]octan-2-one (6g).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6g** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 2-methylphenylallene (**5g**)[29a] (52.0 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to provide **6g** (56.0 mg, 82%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.55; M.p. 158–159 °C (99% ee); $[\alpha]_D^{24}$ = +137.2 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 2985, 2976, 2922, 1744, 1725, 1315, 1159, 1075 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.04 (s, 9H, $C(CH_3)_3$), 1.66 (s, 3H, CH_3), 2.00–2.05 (m, 1H, CH_2), 2.32–2.40 (m, 1H, CH_2), 2.42 (s, 3H, CH_3) 2.50–2.56 (m, 1H, CH_2), 2.67–2.76 (m, 1H, CH_2), 4.35 (s, 1H, CH), 4.91 (s, 1H, C10–H), 5.10 (s, 1H, C10–H), 7.08–7.11 (m, 3H, Ar), 7.23 (m, 1H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.6 (CH_3), 23.5 (CH_3), 27.2 ($C(CH_3)_3$), 34.3 (CH_2), 39.8 (CH_2), 50.5 (CH), 82.2 (C), 83.6 (C), 92.1 (C), 108.5 (CH_2), 126.8 (CH), 127.0 (CH), 127.2 (CH), 129.8 (CH), 134.9 (C), 141.6 (C), 157.4 (C), 164.9 (C), 200.7 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{26}O_4Na$ $[M + Na]^+$ 365.1723, found 365.1724. Anal. Calcd for $C_{21}H_{26}O_4$: C, 73.66; H, 7.65. Found: C, 73.38; H, 7.62.

The enantiomeric excess of **6g** was determined to be 99% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 205 nm): t_R (major) = 16.8 min; t_R (minor) = 22.0 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(3-methoxyphenyl)-5-methyl-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6h).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6h** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 3-methoxyphenylallene (**5h**)[29b] (58.4 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to afford **6h** (46.5 mg, 65%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.50; M.p. 144–145 °C (98% ee); $[\alpha]_D^{20}$ = +88.6 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 3001, 2978, 2936, 1746, 1725, 1598, 1489, 1311, 1247, 1077 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.08 (s, 9H, $C(CH_3)_3$), 1.74 (s, 3H, CH_3), 2.00–2.04 (m, 1H, CH_2), 2.32–2.39 (m, 1H, CH_2), 2.49–2.55 (m, 1H, CH_2), 2.62–2.69 (m, 1H, CH_2), 3.76 (s, 3H, CH_3), 3.96 (t, *J* = 2.0 Hz, 1H, CH), 5.00 (d, *J* = 1.6 Hz, 1H, C10–H), 5.13 (d, *J* = 1.6 Hz, 1H, C10–H), 6.75–6.85 (m, 3H, Ar), 7.17 (t, *J* = 7.52 Hz, 1H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.6 (CH_3), 27.3 ($C(CH_3)_3$), 34.4 (CH_2), 39.8 (CH_2), 55.2 (OCH_3), 56.3 (CH), 82.1 (C), 83.5 (C), 92.0 (C), 109.1 (CH_2), 112.6 (CH), 113.6 (CH), 120.4 (CH), 129.4 (CH), 143.8 (C), 156.7 (C), 159.5 (C), 164.7 (C), 200.6 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{26}O_5Na$ $[M + Na]^+$ 381.1673, found 381.1673. Anal. Calcd for $C_{21}H_{26}O_5$: C, 70.37; H, 7.31. Found: C, 70.12; H, 7.27.

The enantiomeric excess of **6h** was determined to be 98% by HPLC analysis using a Daicel Chiralpak IC column (19 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 43.1 min; t_R (major) = 53.1 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(2-methoxyphenyl)-5-methyl-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6i).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6i** was prepared from α-diazo-β-ketoester **4a** (48.0 mg, 0.20 mmol) and 2-methoxyphenylallene (**5i**)[29b] (58.4 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to give **6i** (45.0 mg, 63%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.45; M.p. 134–135 °C (83% ee); $[\alpha]_D^{24}$ = +114.7 (*c* 1.0, $CHCl_3$); IR (KBr): ν = 3001, 2977, 2932, 1746, 1726, 1492, 1311, 1247, 1077 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.01 (s, 9H, $C(CH_3)_3$), 1.64 (s, 3H, CH_3), 2.00–2.05 (m, 1H, CH_2), 2.31–2.39 (m, 1H, CH_2), 2.47–2.53 (m, 1H, CH_2), 2.70–2.76 (m, 1H, CH_2), 3.84 (s, 3H, CH_3), 4.83 (s, 1H, CH), 4.96 (s, 1H, C10–H), 5.06 (s, 1H, C10–H), 6.84–6.88 (m, 2H, Ar), 7.15–7.17 (m, 1H, Ar), 7.25 (d, *J* = 7.1 Hz, 1H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.5 (CH_3), 27.2 ($C(CH_3)_3$), 34.4 (CH_2), 40.0 (CH_2), 46.3 (OCH_3), 55.4 (CH), 81.7 (C), 83.6 (C), 92.0 (C), 108.1 (CH_2), 110.0 (CH), 121.2 (CH), 127.7 (CH), 128.1 (CH), 131.6 (C), 156.1 (C), 157.4 (C), 165.1 (C), 200.8 (C); HRMS (ESI) *m*/*z* calcd for $C_{21}H_{26}O_5Na$ $[M + Na]^+$ 381.1673, found 381.1672. Anal. Calcd for $C_{21}H_{26}O_5$: C, 70.37; H, 7.31. Found: C, 70.17; H, 7.28.

The enantiomeric excess of **6i** was determined to be 83% by HPLC analysis using a Daicel Chiralpak AD-H column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (major) = 7.4 min; t_R (minor) = 10.7 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-6-methylene-7-phenyl-8-oxabicyclo[3.2.1]octan-2-one (6j).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6j** was prepared from α-diazo-β-ketoester **4b**[9a] (45.2 mg,

0.20 mmol) and phenylallene (**5a**) (46.4 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to provide **6j** (50.0 mg, 80%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.50; M.p. 139–142 °C (96% ee); $[\alpha]_D^{24}$ = +110.4 (*c* 1.1, $CHCl_3$); IR (KBr): ν = 2980, 2929, 1744, 1717, 1367, 1312, 1181, 1152, 1094, 1058, 700 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.07 (s, 9H, $C(CH_3)_3$), 2.04–2.08 (m, 1H, CH_2), 2.48–2.58 (m, 2H, CH_2), 2.63–2.70 (m, 1H, CH_2), 3.94 (d, *J* = 1.2 Hz, 1H, CH), 4.99 (s, 1H, C10–H), 5.11 (br s, 1H, CH), 5.23 (s, 1H, C10–H), 7.21–7.28 (m, 5H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.3 ($C(CH_3)_3$), 33.4 (CH_2), 33.6 (CH_2), 55.3 (CH), 78.7 (CH), 82.3 (C), 94.1 (C), 109.8 (CH_2), 127.1 (CH), 128.3 (CH), 128.4 (CH), 141.9 (C), 153.4 (C), 164.5 (C), 200.4 (C); HRMS (ESI) *m*/*z* calcd for $C_{19}H_{22}O_4Na$ $[M + Na]^+$ 337.1411, found 337.1410.

The enantiomeric excess of **6j** was determined to be 96% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.5 mL min^{-1}, 205 nm): t_R (minor) = 13.5 min; t_R (major) = 35.2 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(4-methoxyphenyl)-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6k).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6k** was prepared from α-diazo-β-ketoester **4b** (45.2 mg, 0.20 mmol) and 4-methoxyphenylallene (**5c**) (58.4 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to afford **6k** (51.4 mg, 75%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.45; M.p. 130–132 °C (96% ee); $[\alpha]_D^{24}$ = +93.3 (*c* 1.0, $CHCl_3$); IR (KBr): ν = 3001, 2981, 2961, 1745, 1719, 1607, 1509, 1242, 1065 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.11 (s, 9H, $C(CH_3)_3$), 2.02–2.07 (m, 1H, CH_2), 2.45–2.57 (m, 2H, CH_2), 2.62–2.71 (m, 1H, CH_2), 3.26 (s, 3H, CH_3), 3.91 (s, 1H, CH), 4.98 (t, *J* = 1.6 Hz, 1H, C10–H), 5.10 (br s, 1H, CH), 5.23 (t, *J* = 1.6 Hz, 1H, C10–H), 6.78–6.82 (m, 2H, Ar), 7.13–7.16 (m, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.4 ($C(CH_3)_3$), 33.4 (CH_2), 33.6 (CH_2), 54.6 (OCH_3), 55.3 (CH), 78.6 (CH), 82.2 (C), 94.2 (C), 109.5 (CH_2), 113.7 (CH), 129.5 (CH), 134.1 (C), 153.6 (C), 158.7 (C), 164.5 (C), 200.6 (C); HRMS (ESI) *m*/*z* calcd for $C_{20}H_{24}O_5Na$ $[M + Na]^+$ 367.1516, found 367.1516. Anal. Calcd for $C_{20}H_{24}O_5$: C, 69.75; H, 7.02. Found: C, 69.58; H, 6.99.

The enantiomeric excess of **6k** was determined to be 96% by HPLC analysis using a Daicel Chiralpak AD-H column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 10.6 min; t_R (major) = 17.0 min.

(1*R,5*R**,7*R**)-7-(4-Bromophenyl)-1-*tert*-butoxycarbonyl-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6l).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6l** was prepared from α-diazo-β-ketoester **4b** (45.2 mg, 0.20 mmol) and 4-bromophenylallene (**5d**) (78.0 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to give **6l** (57.4 mg, 73%) as a pale yellow solid; R_f (7 : 3 hexane–EtOAc) = 0.40; M.p. 157–159 °C (92% ee); $[\alpha]_D^{22}$ = +74.6 (*c* 1.0, $CHCl_3$); IR (KBr): ν = 2981, 1745, 1723, 1482, 1369, 1311, 1159, 1094, 1064 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.12 (s, 9H, $C(CH_3)_3$), 2.04–2.09 (m, 1H, CH_2), 2.50–2.69 (m, 3H, CH_2), 3.92 (t, *J* = 1.2 Hz, 1H, CH), 4.99 (t, *J* = 1.6 Hz, 1H, C10–H), 5.11 (br s, 1H, CH), 5.26 (t, *J* = 1.6 Hz, 1H, C10–H), 7.12–7.15 (m, 2H, Ar), 7.39–7.43 (m, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.5 ($C(CH_3)_3$), 33.4 (CH_2), 33.7 (CH_2), 54.7 (CH), 78.8 (CH), 82.8 (C), 94.1 (C), 110.4 (CH_2), 121.2 (C), 130.2 (CH), 131.6 (CH), 141.1 (C), 153.0 (C), 164.4 (C), 200.3 (C); HRMS (ESI) *m*/*z* calcd for $C_{19}H_{21}BrO_4Na$ $[M + Na]^+$ 415.0514, found 415.0526. Anal. Calcd for $C_{19}H_{21}BrO_4$: C, 58.03; H, 5.38; Br, 20.32. Found: C, 57.76; H, 5.32; Br, 20.04.

The enantiomeric excess of **6l** was determined to be 92% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 16.0 min; t_R (major) = 45.1 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(4-(trifluoromethyl)-phenyl)-6-methylene-8-oxabicyclo[3.2.1]octan-2-one (6m).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6m** was prepared from α-diazo-β-ketoester **4b** (45.2 mg, 0.20 mmol) and 4-(trifluoromethyl)phenylallene (**5e**) (73.7 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to provide **6m** (52.0 mg, 68%) as a pale yellow solid; R_f (7 : 3 hexane–EtOAc) = 0.45; M.p. 164–165 °C (98% ee); $[\alpha]_D^{22}$ = +150.6 (*c* 0.9, $CHCl_3$); IR (KBr): ν = 2995, 2987, 2952, 1747, 1724, 1617, 1423, 1326, 1162, 1129, 1110, 1096, 1069 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.01 (s, 9H, $C(CH_3)_3$), 1.99–2.04 (m, 1H, CH_2), 2.44–2.63 (m, 3H, CH_2), 3.95 (d, *J* = 1.6 Hz, 1H, CH), 4.94 (s, 1H, C10–H), 5.07 (br s, 1H, CH), 5.22 (s, 1H, C10–H), 7.31 (d, *J* = 7.9 Hz, 2H, Ar), 7.47 (d, *J* = 7.9 Hz, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$) δ 27.3 ($C(CH_3)_3$), 33.2 (CH_2), 33.5 (CH_2), 54.8 (CH), 78.7 (CH), 82.7 (C), 93.9 (C), 110.5 (CH_2), 125.3 (CH), 128.1 (C), 128.7 (CH), 129.2 (C), 145.8 (C), 152.6 (C), 164.2 (C), 199.9 (C); HRMS (ESI) *m*/*z* calcd for $C_{20}H_{21}F_3O_4Na$ $[M + Na]^+$ 405.1393, found 405.1392.

The enantiomeric excess of **6m** was determined to be 98% by HPLC analysis using a Daicel Chiralpak IC column (3 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 6.8 min; t_R (major) = 13.7 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-6-methylene-7-(2-methylphenyl)-8-oxabicyclo[3.2.1]octan-2-one (6n).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6n** was prepared from α-diazo-β-ketoester **4b** (45.2 mg, 0.20 mmol) and 2-methylphenylallene (**5g**) (52.0 mg, 0.40 mmol). The crude product was purified using column chromatography (silica gel, 8 : 2 hexane–EtOAc) to afford **6n** (49.6 mg, 76%) as a white solid; R_f (7 : 3 hexane–EtOAc) = 0.50; M.p. 111–113 °C (99% ee); $[\alpha]_D^{24}$ = +128.9 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 2981, 2953, 2936, 1722, 1367, 1301, 1161, 1090, 1076, 761 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.06 (s, 9H, $C(CH_3)_3$), 2.05–2.10 (m, 1H, CH_2), 2.44 (s, 3H, CH_3), 2.50–2.60 (m, 2H, CH_2), 2.68–2.74 (m, 1H, CH_2), 4.28 (d, *J* = 1.6 Hz, 1H, CH), 4.93–4.94 (m, 1H, C10–H), 5.11 (br s, 1H, CH), 5.21 (s, 1H, C10–H), 7.09–7.13 (m, 3H, Ar), 7.24–7.26 (m, 1H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.5 (CH_3), 27.2 ($C(CH_3)_3$), 33.4 (CH_2), 33.5 (CH_2), 49.5 (CH), 78.8 (CH), 82.3 (C), 94.3 (C), 109.2 (CH_2), 126.9 (CH), 127.4 (CH), 128.7 (CH), 129.7 (CH), 135.2 (C), 141.0 (C), 153.9 (C), 164.6 (C), 200.4 (C);

HRMS (ESI) *m/z* calcd for $C_{20}H_{24}O_4Na$ $[M + Na]^+$ 351.1566, found 351.1567. Anal. Calcd for $C_{20}H_{24}O_4$: C, 73.15; H, 7.37. Found: C, 72.93; H, 7.41.

The enantiomeric excess of **6n** was determined to be 99% by HPLC analysis using a Daicel Chiralpak IC column (3 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (minor) = 9.9 min; t_R (major) = 18.2 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-6-methylene-5,7-diphenyl-8-oxabicyclo[3.2.1]octan-2-one (6o).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6o** was prepared from α-diazo-β-ketoester **4c**[5d] (60.4 mg, 0.20 mmol) and phenylallene (**5a**) (46.4 mg, 0.40 mmol). The crude product was purified using column chromatography (Wakogel® C-200, 8 : 2 hexane–EtOAc) to give **6o** (74.9 mg, 96%) as a white solid; R_f (8 : 2 hexane–EtOAc) = 0.60; M.p. 148–150 °C (97% ee); $[\alpha]_D^{23}$ = +62.0 (*c* 1.2, $CHCl_3$); IR (KBr): ν = 2975, 1752, 1731, 1368, 1311, 1158, 1078, 700 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.10 (s, 9H, $C(CH_3)_3$), 2.64–2.70 (m, 3H, CH_2), 2.88–2.95 (m, 1H, CH_2), 4.16 (m, 1H, CH), 5.02 (d, *J* = 1.6 Hz, 1H, C10–H), 5.12 (d, *J* = 1.6 Hz, 1H, C10–H), 7.19–7.27 (m, 5H, Ar), 7.32–7.36 (m, 1H, Ar), 7.40–7.44 (m, 2H, Ar), 7.69–7.71 (m, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.3 ($C(CH_3)_3$), 34.2 (CH_2), 38.9 (CH_2), 56.3 (CH), 82.3 (C), 86.0 (C), 91.9 (C), 112.0 (CH_2), 125.4 (CH), 127.1 (CH), 127.8 (CH), 128.4 (CH), 128.5 (CH), 128.6 (CH), 140.7 (C), 141.9 (C), 155.8 (C), 164.6 (C), 200.2 (C); HRMS (ESI) *m/z* calcd for $C_{25}H_{26}O_4Na$ $[M + Na]^+$ 413.1724, found 413.1723. Anal. Calcd for $C_{25}H_{26}O_4$: C, 76.90; H, 6.71. Found: C, 76.81; H, 6.74.

The enantiomeric excess of **6o** was determined to be 97% by HPLC analysis using a Daicel Chiralpak IC column (9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (major) = 17.3 min; t_R (minor) = 24.3 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(4-methoxyphenyl)-6-methylene-5-phenyl-8-oxabicyclo[3.2.1]octan-2-one (6p).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6p** was prepared from α-diazo-β-ketoester **4c** (60.4 mg, 0.20 mmol) and 4-methoxyphenylallene (**5c**) (58.4 mg, 0.40 mmol). The crude product was purified by column chromatography (Wakogel® C-200, 8 : 2 hexane–EtOAc) to provide **6p** (79.0 mg, 94%) as a white solid; R_f (8 : 2 hexane–EtOAc) = 0.50; M.p. 154–155 °C (94% ee); $[\alpha]_D^{20}$ = +83.2 (*c* 1.0, $CHCl_3$); IR (KBr): ν = 2979, 2930, 1733, 1610, 1511, 1311, 1244, 1158, 1081 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.15 (s, 9H, $C(CH_3)_3$), 2.62–2.69 (m, 3H, CH_2), 2.84–2.90 (m, 1H, CH_2), 3.76 (s, 3H, CH_3), 4.14 (s, 1H, CH), 5.02 (d, *J* = 1.2 Hz, 1H, C10–H), 5.12 (d, *J* = 1.2 Hz, 1H, C10–H), 6.79–6.81 (m, 2H, Ar), 7.17–7.19 (m, 2H, Ar), 7.32–7.36 (m, 1H, Ar), 7.41–7.44 (m, 2H, Ar), 7.69–7.71 (m, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.4 ($C(CH_3)_3$), 34.3 (CH_2), 39.0 (CH_2), 55.3 (OCH_3), 55.7 (CH), 82.3 (C), 85.9 (C), 91.9 (C), 111.7 (CH_2), 113.8 (CH), 125.4 (CH), 127.8 (CH), 128.5 (CH), 129.6 (CH), 134.1 (C), 140.8 (C), 156.0 (C), 158.7 (C), 164.7 (C), 200.4 (C); HRMS (ESI) *m/z* calcd for $C_{26}H_{28}O_5Na$ $[M + Na]^+$ 443.1827, found: 443.1840. Anal. Calcd for $C_{26}H_{28}O_5$: C, 74.26; H, 6.71. Found: C, 73.81; H, 6.86.

The enantiomeric excess of **6p** was determined to be 94% by HPLC analysis using a Daicel Chiralpak AD-H column (AD-H + AD-H, 9 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (major) = 18.9 min; t_R (minor) = 20.5 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-7-(4-(trifluoromethyl)-phenyl)-6-methylene-5-phenyl-8-oxabicyclo[3.2.1]octan-2-one (6q).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6q** was prepared from α-diazo-β-ketoester **4c** (60.4 mg, 0.20 mmol) and 4-(trifluoromethyl)phenylallene (**5e**) (73.7 mg, 0.40 mmol). The crude product was purified using column chromatography (Wakogel® C-200, 8 : 2 hexane–EtOAc) to afford **6q** (81.0 mg, 88%) as a white solid; R_f (8 : 2 hexane–EtOAc) = 0.45; M.p. 166–167 °C (99% ee); $[\alpha]_D^{22}$ = +69.9 (*c* 0.8, $CHCl_3$); IR (KBr): ν = 2983, 2931, 1747, 1723, 1616, 1480, 1322, 1123, 1059 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.11 (s, 9H, $C(CH_3)_3$), 2.66–2.73 (m, 3H, CH_2), 2.84–2.91 (m, 1H, CH_2), 4.24 (s, 1H, CH), 5.04 (s, 1H, C10–H), 5.18 (s, 1H, C10–H), 7.34–7.46 (m, 5H, Ar), 7.54 (d, *J* = 7.5 Hz, 2H, Ar), 7.68 (d, *J* = 7.5 Hz, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.3 ($C(CH_3)_3$), 34.2 (CH_2), 38.9 (CH_2), 55.9 (CH), 82.8 (C), 86.1 (C), 91.7 (C), 112.6 (CH_2), 125.3 (CH), 125.4 (CH), 128.0 (CH), 128.5 (C), 128.6 (CH), 128.8 (CH), 129.3 (C), 140.4 (C), 145.8 (C), 155.1 (C), 164.3 (C), 199.8 (C); HRMS (ESI) *m/z* calcd for $C_{26}H_{25}F_3O_4Na$ $[M + Na]^+$ 481.1597, found 481.1590. Anal. Calcd for $C_{26}H_{25}F_3O_4$: C, 68.11; H, 5.50; F, 12.43. Found: C, 67.99; H, 5.60; F, 12.4.

The enantiomeric excess of **6q** was determined to be 99% by HPLC analysis using a Daicel Chiralpak IC column (50 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (major) = 28.6 min; t_R (minor) = 34.2 min.

(1*R,5*R**,7*R**)-1-*tert*-Butoxycarbonyl-6-methylene-7-(3-methylphenyl)-5-phenyl-8-oxabicyclo[3.2.1]octan-2-one (6r).** According to the typical procedure for Rh(II)-catalyzed enantioselective 1,3-dipolar cycloaddition, **6r** was prepared from α-diazo-β-ketoester **4c** (60.4 mg, 0.20 mmol) and 2-methylphenylallene (**5g**) (52.0 mg, 0.40 mmol). The crude product was purified using column chromatography (Wakogel® C-200, 8 : 2 hexane–EtOAc) to give **6r** (79.2 mg, 98%) as a white solid; R_f (8 : 2 hexane–EtOAc) = 0.50; M.p. 154–155 °C (99% ee); $[\alpha]_D^{19}$ = +82.7 (*c* 1.0, $CHCl_3$); IR (KBr): ν = 2980, 2922, 1747, 1727, 1368, 1310, 1159, 1084, 755 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 1.09 (s, 9H, $C(CH_3)_3$), 2.45 (s, 3H, CH_3), 2.64–2.70 (m, 3H, CH_2), 2.90–2.99 (m, 1H, CH_2), 4.51 (s, 1H, CH), 4.95 (d, *J* = 1.6 Hz, 1H, C10–H), 5.07 (d, *J* = 1.6 Hz, 1H, C10–H), 7.06–7.14 (m, 3H, Ar), 7.26–7.29 (m, 1H, Ar), 7.32–7.36 (m, 1H, Ar), 7.41–7.44 (m, 2H, Ar), 7.70–7.72 (m, 2H, Ar); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.6 (CH_3), 27.3 ($C(CH_3)_3$), 34.1 (CH_2), 38.9 (CH_2), 50.5 (CH), 82.4 (C), 86.0 (C), 91.9 (C), 111.3 (CH_2), 125.4 (CH), 126.8 (CH), 127.0 (CH), 127.6 (CH), 127.8 (CH), 128.5 (CH), 129.8 (CH), 135.2 (C), 140.7 (C), 141.0 (C), 156.2 (C), 164.7 (C), 200.3 (C); HRMS (ESI) *m/z* calcd for $C_{26}H_{28}O_4Na$ $[M + Na]^+$ 427.1880, found: 427.1891. Anal. Calcd for $C_{26}H_{28}O_4$: C, 77.20; H, 6.98. Found: C, 76.81; H, 6.97.

The enantiomeric excess of **6r** was determined to be 99% by HPLC analysis using a Daicel Chiralpak IC column

(3 : 1 hexane–2-propanol, flow rate = 1.0 mL min^{-1}, 226 nm): t_R (major) = 7.2 min; t_R (minor) = 12.8 min.

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