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Inverse electron demand asymmetric cycloadditions of cyclic carbonyl ylides catalyzed by chiral Lewis acids—Scope and limitations of diazo and olefinic substrates

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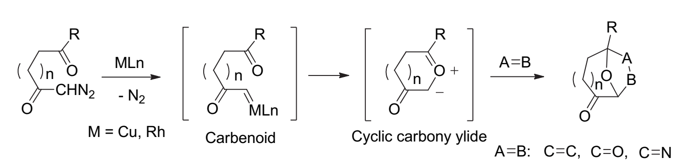
High enantioselectivities (94–96% ee) were obtained for the inverse electron-demand 1,3-dipolar cycloadditions between cyclohexyl vinyl ether and 2-benzopyrylium-4-olate generated via $Rh_2(OAc)_4$-catalyzed decomposition of *o*-methoxycarbonyl-α-diazoacetophenone. The reactions were effectively catalyzed by $Eu(OTf)_3$, $Ho(OTf)_3$, or $Gd(OTf)_3$ complexes (10 mol %) of chiral 2,6-bis[(4*S*,5*S*)-4,5-diphenyl-2-oxazolinyl]pyridine. The reactions with the other electron-rich dipolarophiles such as allyl alcohol, 2,3-dihydrofuran, and butyl-*tert*-butyldimethylsilylketene acetal showed moderate enanantioselectivities (60–73% ee). Good to high enantioselectivities (73–97% ee) were also obtained for the cycloadditions between 3-acyl-2-benzopyrylium-4-olates, generated from methyl 2-(2-diazo-1,3-dioxoalkyl)benzoates and butyl or cyclohexyl vinyl ethers, in the presence of binaphthyldiimine (BINIM)–Ni(II) complexes (10 mol %). Under similar conditions, the reaction between methyl 2-(2-diazo-1,3-dioxohexyl)benzoate and 2,3-dihydrofuran was highly *endo*-selective, and moderately enantioselective (70% ee). For the BINIM–Ni(II)-catalyzed reactions of cyclohexyl vinyl ether, the use of an epoxyindanone as the 3-acyl-2-benzopyrylium-4-olate precursor revealed that the chiral Lewis acid can function as a catalyst for asymmetric induction. The scope of the cyclic carbonyl ylides was extended to those generated from 1-diazo-2,5-pentanedione derivatives, which were reacted with butyl or TBS vinyl ether and catalyzed using the (4*S*,5*S*)-Pybox-4,5-Ph_2–$Lu(OTf)_3$ complex to give good levels of asymmetric inductions (75–84% ee).

1. Introduction

Tandem Rh(II)-catalyzed intramolecular carbonyl ylide formation followed by 1,3-dipolar cycloaddition of α-diazocarbonyl compounds with dipolarophiles,[1] which can efficiently provide epoxy-bridged complex polycyclic products in a one-pot reaction (Scheme 1), has been applied toward the syntheses of various biologically important oxygen-containing polycyclic natural products, such as brevicomin,[2] zaragozic acids,[3] komaroviquinone,[4] polygalolides,[5] pseudolaric acid A,[6] and aspidophytine[7] (Fig. 1). To improve the asymmetric synthesis of optically active oxygen-containing polycyclic compounds, Hodgson[8] and Hashimoto[9] have independently developed a highly enantioselective variant of this methodology featuring a chiral Rh(II)-associated carbonyl ylide in the transition state. In contrast, our laboratory has pursued a different approach—rare earth metal complexes of chiral 2,6-(oxazolinyl)-pyridine (Pybox)[10] were employed as chiral Lewis acids to catalyze the enantioselective cycloadditions between 2-benzopyrylium-4-olate and electron-deficient carbonyl and olefinic dipolarophiles. We have recently reported on the first successful examples of chiral Lewis acid-catalyzed inverse electron-demand cycloadditions between 2-benzopyrylium-4-olates and vinyl ether derivatives with high levels of asymmetric induction.[11] In this paper, we describe the full account of our investigations on the inverse electron-demand cycloadditions of cyclic carbonyl ylides, along with the scope and limitations of our methodology with



Scheme 1.

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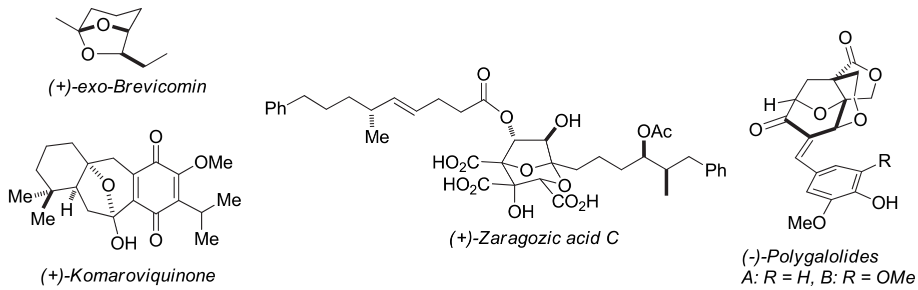


Figure 1. Naturally occurring epoxy-bridged polycyclic compounds.

regards to the several electron-rich olefinic dipolarophiles and diazo substrates as the carbonyl ylide precursors. It is important to note that the range of diazo substrates have been extended to include several 1-diazo-2,5-pentanedione derivatives with good levels of asymmetric induction. Insights into the mechanism of the Rh(II)- and chiral Lewis acid catalysts, using the corresponding epoxyindanone as the carbonyl ylide precursor, are also presented.

2. Results and discussion

2.1. Reaction of *o*-methoxycarbonyl-α-diazoacetophenone with vinyl ethers

Initially, we examined the reaction between butyl vinyl ether (**2a**) and *o*-methoxycarbonyl-α-diazoacetophenone (**1**), as a precursor of 2-benzopyrylium-4-olate, in the presence of chiral Lewis acids that were prepared from 2,6-bis[(4*S*,5*S*)-4,5-diphenyl-1,3-oxazolin-2-yl]pyridine ((4*S*,5*S*)-Pybox-4,5-Ph_2, Fig. 2) and lanthanoid triflates (Scheme 2). The reaction was carried out by adding a solution of diazoacetophenone **1** to vinyl ether **2a** and $Rh_2(OAc)_4$ (2 mol %) in refluxing CH_2Cl_2 over a period of 1 h in the presence of the (4*S*,5*S*)-Pybox-4,5-Ph_2–lanthanoid metal complex (10 mol %), which was prepared in advance by mixing the ligand and the corresponding triflates in THF for 2 h followed by drying in vacuo. The influence of the ionic radius of the lanthanoid metals on the enantio- and diastereoselectivities, and the yields of the cycloadducts are shown in Table 1 (entries 1–9) and Figure 3. Although strong correlations were not observed (Fig. 3), lanthanoid triflates that exhibited higher enantioselectivities generally corresponded to higher yields. Good enantioselectivities (81–85% ee) were obtained for reactions involving $Eu(OTf)_3$, $Gd(OTf)_3$, $Ho(OTf)_3$ $Er(OTf)_3$, and $Tm(OTf)_3$. The nature of the lanthanoid triflates, however, did not significantly affect the diastereoselectivities. In regards to the R group of the vinyl ether (entries 3 and 10–14), a series of (4*S*,5*S*)-Pybox-Ph_2–Eu(III)-catalyzed reactions in CH_2Cl_2 (commercial grade) under refluxing conditions revealed that a cyclohexyl substituent (entry 14) gave the highest enantio- (95% ee)[12] and diastereoselectivities (*endo*/*exo*=88:12).[13] Interestingly, both enantioselectivity and yield were reduced when dried and purified CH_2Cl_2 (via distillation over $CaCl_2$, then CaH_2) (entry 15) was used as the reaction solvent—the enantioselectivity and yield, however, were restored by the addition of MeOH (10 mol %) to the dried and purified CH_2Cl_2 (entries 16 and 17). Similarly, extremely high enantioselectivities were obtained for the cyclohexyl vinyl ether reactions in commercial CH_2Cl_2 using Gd(III)- and Ho(III)-complexes (entries 18 and 19, respectively).

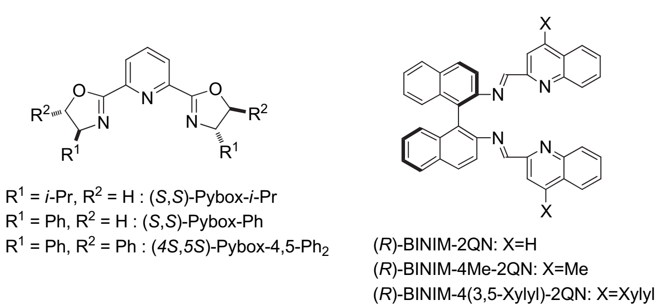
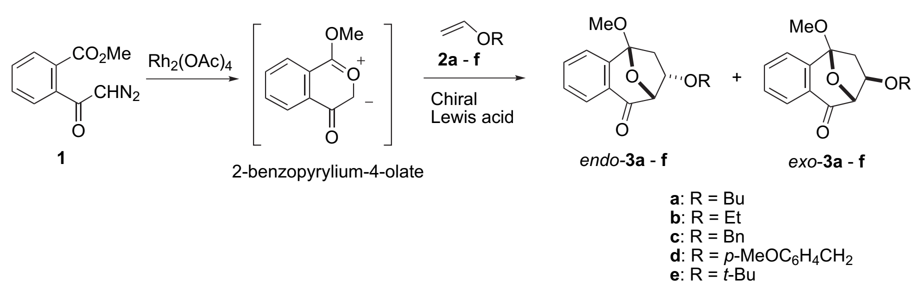


Figure 2. Structures of chiral Pybox and BINIM ligands.

2.2. Reaction of *o*-methoxycarbonyl-α-diazoacetophenone with other electron-rich dipolarophiles

To investigate the scope of the electron-rich dipolarophiles for diazo substrate **1**, reactions were carried out using monosubstituted olefins **4**–**9** in the presence of Pybox-Ph_2–Eu(III) (10 mol %) (Scheme 3, Table 2). In contrast to the alkyl vinyl ethers, TBS vinyl ether (**4**), which possesses a slightly weaker electron-releasing character, was somewhat unreactive under similar conditions, afforded the *endo*-cycloadduct in a low yield and enantioselectivity (entry 1). Accordingly, weak electron-releasing olefins such as vinyl propanoate (**5**), 1-pentene (**6**), and allyl butyl ether (**7**) did not afford the corresponding cycloadducts. Surprisingly, allyl alcohol (**8**), which presumably possesses an electron-releasing character similar to that of allyl butyl ether (**7**), was reactive in the presence of the (4*S*,5*S*)-Pybox-Ph_2–Eu(III) catalyst in



Scheme 2.

Table 1
Reactions between diazoacetophenone **1** and olefins **2a–f** catalyzed by chiral (4*S*,5*S*)-Pybox-4,5-Ph_2–$M(OTf)_3$ complexes[a]

Entry	R	M (Ionic Radius (Å))	Distillation of CH_2Cl_2[b]	Additive	Temp (°C)	Yield (%)	*endo*:*exo*[c]	ee[d] (%)
1	Bu	La (1.032)	No	None	Reflux	87	76:24	51
2	Bu	Sm (0.958)	No	None	Reflux	74	79:21	59
3	Bu	Eu (0.947)	No	None	Reflux	94	81:19	81
4	Bu	Gd (0.938)	No	None	Reflux	Quant	81:19	85
5	Bu	Tb (0.923)	No	None	Reflux	65	79:21	67
6	Bu	Ho (0.901)	No	None	Reflux	89	79:21	85
7	Bu	Er (0.890)	No	None	Reflux	97	79:21	84
8	Bu	Tm (0.880)	No	None	Reflux	78	77:23	81
9	Bu	Yb (0.868)	No	None	Reflux	80	75:25	67
10	Et	Eu (0.947)	No	None	Reflux	92	83:17	83
11	Bn	Eu (0.947)	Yes	MeOH (10 mol %)	Reflux	61	80:20	61
12	PMB[e]	Eu (0.947)	Yes	MeOH (10 mol %)	Reflux	64	82:18	79
13	*t*-Bu	Eu (0.947)	No	None	Reflux	91	87:13	88
14	Cy[f]	Eu (0.947)	No	None	Reflux	Quant	88:12	95
15	Cy[f]	Eu (0.947)	Yes	None	Reflux	63	89:11	69
16	Cy[f]	Eu (0.947)	Yes	MeOH (10 mol %)	Reflux	Quant	89:11	96
17[g]	Cy[f]	Eu (0.947)	Yes	MeOH (10 mol %)	Reflux	99	90:10	95
18	Cy[f]	Gd (0.938)	No	None	Reflux	93	88:12	94
19	Cy[f]	Ho (0.901)	No	None	Reflux	99	88:12	96

[a] The reactions were carried out by adding a solution of **1** in CH_2Cl_2 to a suspension of **2a–f**, $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, and Pybox–$M(OTf)_3$ complexes (10 mol %) in CH_2Cl_2 under reflux over a period of 1 h.
[b] Yes: CH_2Cl_2 was dried and purified by distillation with $CaCl_2$, then CaH_2. No: commercially available CH_2Cl_2 was used without further purifications.
[c] Determined by ^1H NMR.
[d] Enantiomeric excess of the *endo*-adduct was determined using chiral HPLC.
[e] *p*-Methoxybenzyl.
[f] Cyclohexyl.
[g] A mixture of **1** and **2f** in CH_2Cl_2 was added over a period of 1 h.

CH_2Cl_2 under reflux conditions to exclusively afford the *endo*-cycloadduct in a 32% yield with moderate enantioselectivity (entry 2). Moreover, the yield and enantioselectivity were improved (59% and 51% ee, respectively) when the reaction was carried out in refluxing $CHCl_3$ (entry 3).

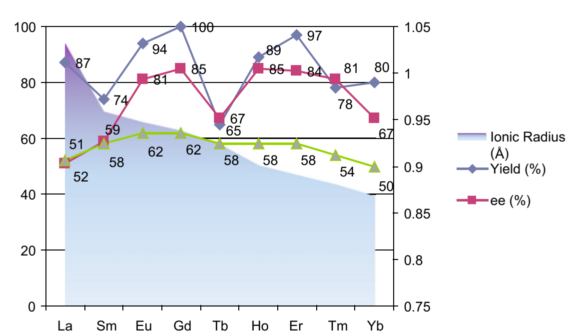


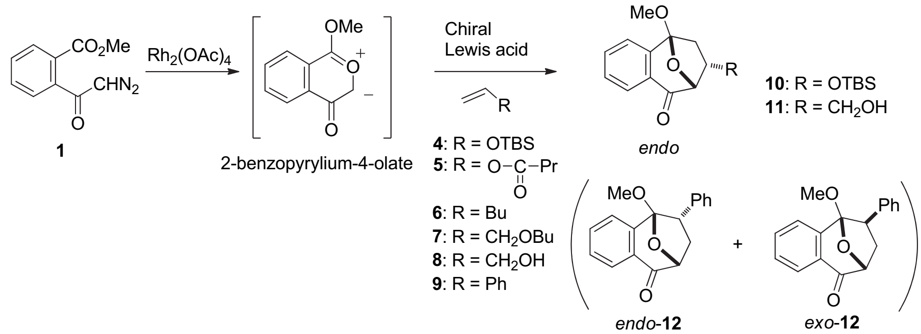
Figure 3. Relationship between the ionic radius of the lanthanoid metals and the enantio- or diastereoselectivities for the reaction between diazoacetophenone **1** and olefin **2a** catalyzed by chiral (4*S*,5*S*)-Pybox-4,5-Ph_2–$M(OTf)_3$ complexes.

Next, the relationship between the lanthanoid metals on the enantioselectivities and yields in refluxing $CHCl_3$ were examined. As shown in Figure 4, the yields varied between 36% and 88%, and did not exhibit any strong correlations to the ionic radii. Although the use of the $Eu(OTf)_3$, $Gd(OTf)_3$, and $Ho(OTf)_3$ complexes exhibited higher enantioselectivities than that of other lanthanoid triflates, the maximum enantioselectivity was merely 55% ee ($Ho(OTf)_3$, entry 4). Subsequent investigations revealed that the addition of basic inorganic salts (10–30 mol %) in combination with the (4*S*,5*S*)-Pybox-Ph_2–Ho(III) catalyst improved the enantioselectivity (up to 60% ee) with reasonable yields (entries 5–7).[27] The (4*S*,5*S*)-Pybox-Ph_2–Eu(III)-catalyzed reaction of styrene (**9**) in CH_2Cl_2 under reflux conditions afforded the alternate regio-isomer with a yield of 22% as a mixture of the *exo*:*endo* diastereomers with low enantioselectivity (entry 8). The regioselectivity was in good agreement with that observed for the reaction of electron-deficient olefinic dipolarophiles such as 3-acryloyl-2-oxazolidinone.

Next, reactions were carried using other electron-releasing olefins such as substituted alkenyl ethers, 2,3-dihydrofuran (**13**), methoxypropene (**14**), and silylketene acetal **15** (Scheme 4, Table 3). In the case of **13**, the (4*S*,5*S*)-Pybox-Ph_2–Eu(III)-catalyzed (10 mol %) reaction in CH_2Cl_2 under reflux conditions gave only the *endo*-cycloadduct in a high yield with 59% ee (entry 1). Upon further investigations using different temperatures and solvents, the enantioselectivity was improved (66% ee, entry 2) using toluene as the solvent and 45 °C as the reaction temperature. Investigations involving various lanthanoid triflates revealed that the combination of $Yb(OTf)_3$ with (4*S*,5*S*)-Pybox-Ph_2 afforded the highest enantioselectivity (67% ee, entry 3).[14] Interestingly, although the (4*S*,5*S*)-Pybox-Ph_2–Eu(III)-catalyzed reaction of methoxypropene (**14**) resulted in a low yield and stereoselectivity (entry 4), the reaction of silylketene acetal **15** in refluxing CH_2Cl_2 afforded the cycloadduct as a mixture of diastereomers (72:28) with a total yield of 54% and ee values of 27% and 53% (major and minor diastereomers, respectively) (entry 5). The enatioselectivities of (4*S*,5*S*)-Pybox-Ph_2–Lu(III)-catalyzed reaction were somewhat improved using a reaction temperature of 45 °C in $CHCl_3$ (entry 7). It is interesting to note that the use of (*S*,*S*)-Pybox-Ph and (*S*,*S*)-Pybox-*i*-Pr as ligands caused a switch of the major diastereomer with diastereoselectivity of up to 76:24 (entries 8 and 9). Moreover, upon a survey of reaction solvents, the use of toluene gave the highest enantioselectivites (about 70% ee) without causing a significant loss in the diastereoselectivity (entries 10–12).

2.3. Reaction of methyl 2-(2-diazo-1,3-dioxoalkyl)benzoates with vinyl esters

To investigate the generality of our methodology on other diazo compounds (Table 4), butyl vinyl ether (**2a**) was reacted with α,α′-dicarbonyl diazo substrate **19**, which was prepared from diazoacetophenone **1** according to the procedure reported by Padwa.[4] To date, catalysts involving various combinations of chiral Pybox ligands and lanthanoid triflates have yet to afford satisfactory



Scheme 3.

Table 2
Reactions between diazoacetophenone **1** and olefins **4**, **8**, and **9** catalyzed by chiral (4*S*,5*S*)-Pybox-4,5-Ph_2–$M(OTf)_3$ complexes[a]

Entry	R′ (**4**, **8**, **9**)	M (Ionic radius (Å))	Solvent	Temp (°C)	Additive (mol %)	Yield (%)	ee[b] (%)
1	OTBS (**4**)	Eu (0.947)	CH_2Cl_2[c]	Reflux	MeOH (10)	13	17
2	CH_2OH (**8**)	Eu (0.947)	CH_2Cl_2[c]	Reflux	MeOH (10)	32	45
3	CH_2OH (**8**)	Eu (0.947)	$CHCl_3$	Reflux	None	59	51
4	CH_2OH (**8**)	Ho (0.901)	$CHCl_3$	Reflux	None	70	55
5	CH_2OH (**8**)	Ho (0.901)	$CHCl_3$	Reflux	K_2CO_3 (30)	61	60
6	CH_2OH (**8**)	Ho (0.901)	$CHCl_3$	Reflux	LiF (30)	73	59
7	CH_2OH (**8**)	Ho (0.901)	$CHCl_3$	Reflux	NaOAc (10)	66	58
8	Ph (**9**)	Eu (0.947)	CH_2Cl_2	Reflux	MeOH (10)	22 (69:31)[d]	10, 20[e]

[a] The reactions were carried out by adding a solution of **1** in CH_2Cl_2 to a suspension of olefins **4**–**9**, $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, and Pybox–$M(OTf)_3$ complexes (10 mol %) over a period of 1 h.
[b] Enantiomeric excess of the *endo*-adduct was determined using chiral HPLC.
[c] Dried and purified by distillation with $CaCl_2$ and then CaH_2.
[d] Diastereomeric ratio.
[e] Enantiomeric excess of the adducts were determined using chiral HPLC (Major, Minor).

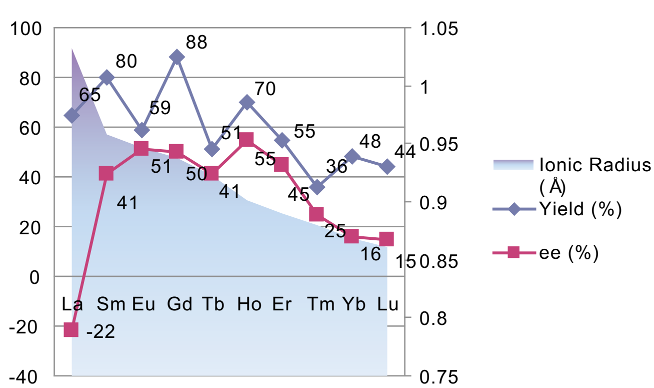
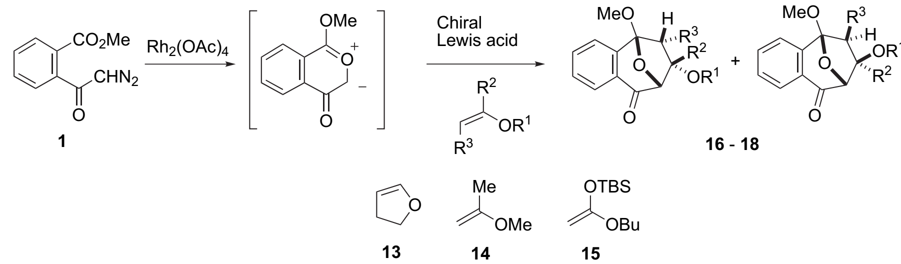


Figure 4. Relationship between the ionic radius of the lanthanide metals and the enantioselectivities and yields for the reaction between diazoacetophenone **1** and olefin **8** catalyzed by chiral (4*S*,5*S*)-Pybox-4,5-Ph_2–$M(OTf)_3$ complexes.

enantioselectivities.[15] However, we have achieved good enantioselectivities (up to 73% ee) with extremely high *endo* selectivity (Table 4, entries 1–3) using a chiral catalyst consisting of $Ni(ClO_4)_2 \cdot 6H_2O$ and optically active binaphthyldiimine (BINIM) ligand (Fig. 2).[16] Raising the temperature for the reactions of **19** in CH_2Cl_2 under reflux conditions increased the enantioselectivities to 92% ee,[12] using the (*R*)-BINIM-4Me-2QN–Ni(II) complex as the Lewis acid (entry 4). Under similar conditions, high enantioselectivity was also obtained for the reaction with cyclohexyl vinyl ether (**2f**, entry 6)—however, a slightly lower enantioselectivity was observed for the reaction with benzyl vinyl ether (**2c**, entry 5). Similar to the reaction of diazo substrate **1**, the use of dried and purified CH_2Cl_2 (distillation with $CaCl_2$, then CaH_2) as the solvent resulted in lowering the enantioselectivity (entry 7), which was recovered to that of commercial CH_2Cl_2 by the addition of MeOH (10 mol %) (entries 8 and 9). Subsequently, the BINIM-4Me-2QN–Ni(II) catalyst was employed for the reactions of several diazo compounds **20**–**27** with vinyl ethers **2c** or **2d** to give the corresponding adducts with good to excellent enantioselectivities (entries 10–18). Among diazo compounds **19**–**27**, those that possess substrates with bulky acyl substituents exhibited relatively higher enantioselectivities (entries 12, and 16).

2.4. Asymmetric induction using epoxyindanone as a carbonyl ylide precursor

Padwa reported that, in the presence of $Rh_2(OAc)_4$, carbonyl ylides that are generated from α,α'-dicarbonyl diazo compounds in the absence of dipolarophiles cyclize to the corresponding epoxyindanones that, upon heating, revert to the carbonyl ylides.[4] Accordingly, diazo compound **23** was cyclized, under similar conditions, to epoxyindanone **B** as the precursor of carbonyl ylide **A**. As a note, the reaction also afforded a small amount of 3,4-dihydro-1*H*-2-benzopyran-1,4-dione derivative as an impurity. Under reflux conditions (CH_2Cl_2) without slow addition of substrates, however, (*R*)-BINIM-4Me-2QN–Ni(II)-catalyzed reaction between diazo substrate **23** and vinyl ether **2f** required a relatively long reaction time (22 h) affording the *endo*-adduct (61% yield) with merely 9% ee. In contrast, slow addition (over a period of 1 h) of epoxyindanone **B** into a solution of vinyl ether **2f** and the Ni(II) catalyst in dry CH_2Cl_2 under reflux conditions gave *endo*-cycloadduct **32f** (60% yield) with 86% ee (Scheme 5). Under the conditions, however, the reaction did not proceed to completion, in which unreacted epoxyindanone **B** was readily hydrolyzed to the 3,4-dihydro-1*H*-2-benzopyran-1,4-dione derivative during chromatographic separation of cycloadduct **32f**. Our results suggest



Scheme 4.

Table 3
Reactions between diazoacetophenone **1** and olefins **13**–**15** catalyzed by chiral (4*S*,5*S*)-Pybox-4,5-Ph_2–$M(OTf)_3$ complexes[a]

Entry	Olefin	M (Å)[b]	Pybox	Solvent	Temp (°C)	Yield (%) (Products)	dr	ee (%)[c]	
								Former	Latter
1	**13**	Eu (0.947)	Pybox-Ph_2	CH_2Cl_2[d]	Reflux	98 (**16**)	>99:1[e]	59	
2	**13**	Eu (0.947)	Pybox-Ph_2	Toluene	45	96 (**16**)	>99:1[e]	66	
3	**13**	Yb (0.868)	Pybox-Ph_2	Toluene	45	86 (**16**)	>99:1[e]	67	
4	**14**	Eu (0.947)	Pybox-Ph_2	CH_2Cl_2[d]	Reflux	23 (**17**)	47:53	15	12
5	**15**	Eu (0.947)	Pybox-Ph_2	CH_2Cl_2[f]	Reflux	54 (**18**)	28:72	53	27
6	**15**	Lu (0.861)	Pybox-Ph_2	CH_2Cl_2[f]	Reflux	41 (**18**)	42:58	56	26
7	**15**	Lu (0.861)	Pybox-Ph_2	$CHCl_3$	45	36 (**18**)	46:54	67	42
8	**15**	Lu (0.861)	Pybox-Ph	$CHCl_3$	45	29 (**18**)	64:36	58	44
9	**15**	Lu (0.861)	Pybox-*i*-Pr	$CHCl_3$	45	24 (**18**)	76:24	65	56
10	**15**	Lu (0.861)	Pybox-*i*-Pr	Toluene	45	68 (**18**)	74:26	72	55
11	**15**	Lu (0.861)	Pybox-*i*-Pr	Toluene[g]	45	63 (**18**)	74:26	70	73
12	**15**	Lu (0.861)	Pybox-*i*-Pr	Toluene[h]	45	49 (**18**)	72:28	70	72

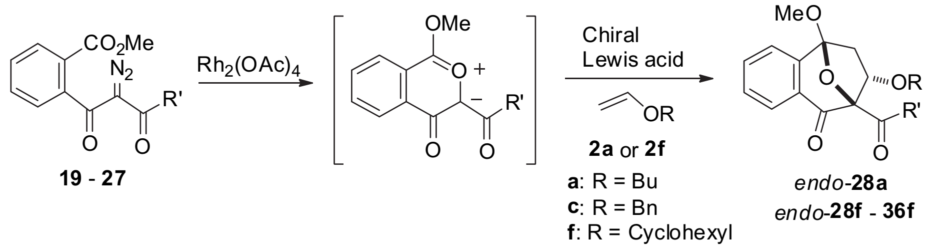
[a] The reactions were carried out by adding a solution of **1** to a suspension of olefins **13**–**15**, $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, and Pybox–$M(OTf)_3$ complexes (10 mol %, 5.0×10^{-3} M calculated from total volume of the solvent used) over a period of 1 h.
[b] Ionic radius.
[c] Enantiomeric excess of the adduct was determined using chiral HPLC.
[d] Commercially available CH_2Cl_2 was used without further purifications.
[e] Only the *endo*-adduct was obtained.
[f] Dried and purified CH_2Cl_2 was used with MeOH (10 mol %) as an additive.
[g] 2.5×10^{-3} M for Pybox-*i*-Pr-Lu$(OTf)_3$.
[h] 10.0×10^{-3} M for Pybox-*i*-Pr-Lu$(OTf)_3$.

that the asymmetric induction is effectively catalyzed by the (*R*)-BINIM-4Me-2QN–Ni(II) complex, and without the participation of $Rh_2(OAc)_4$, which may be involved only in the generation of the carbonyl ylides for reactions of diazocarbonyl compounds as substrates. It should be noted that the use of commercial grade CH_2Cl_2 as a solvent lowered not only yield (40%) but also enantioselectivity (65% ee) in the reaction of epoxyindanone **B** as a carbonyl ylide precursor. This result indicates that commercial grade CH_2Cl_2 or MeOH as an additive in purified CH_2Cl_2 probably did not play an effective role for improvement of yield and enantioselectivity in the chiral Lewis acid-catalyzed cycloaddition step of carbonyl ylides, which were generated from diazocarbonyl compounds. As mentioned above, Hodgson[8] and Hashimoto[9] showed that Rh(II)-associated species could participate in the transition state of the cycloadditions of carbonyl ylides. However, compared with a free carbonyl ylide, the Rh(II)-associated carbonyl ylide would not easily coordinate with a chiral Lewis acid for activation on a basis of frontier orbital theory. Considering from these facts, one possibility for the effect of MeOH as an additive or commercial grade CH_2Cl_2 is that it can be attributed to the presumed coordination of the chiral Lewis acid to the carbonyl ylide via dissociation of the Rh-associated species to a free carbonyl ylide. The unusual dependence between the selectivity and the reaction temperature (raising the temperature increased the enantioselectivity, Table 4, entries 3 vs 4) may be also attributed to the dissociation of the Rh-associated species in the reaction of diazo substrates as carbonyl ylide precursors.

2.5. Reaction of methyl 2-(2-diazo-1,3-dioxohexyl)benzoate with other electron-rich dipolarophiles

To investigate the range of electron-rich dipolarophiles as diazo substrate **19**, reactions were carried out using mono-substituted olefins **4**–**9** and disubstituted alkenyl ethers **13**–**15** and **37** (Scheme 6, Table 5). In comparison to those from diazo compound **1**, carbonyl ylides that were generated from diazo compound **19** exhibited somewhat different reactivities toward the dipolarophiles. In the case of TBS vinyl ether (**4**, entry 2), the yield of the (4*S*,5*S*)-Pybox-Ph_2–Eu$(OTf)_3$–catalyzed reaction with diazo compound **19** was higher (68%) than that with diazo substrate **1** but with similar low enantioselectivity. For vinyl propanoate (**5**), 1-pentene (**6**), allyl butyl ether (**7**), and styrene (**9**) (entries 3–7), the (*R*)-BINIM-4Me-2QN–Ni(II)-catalyzed reactions did afford the corresponding cycloadducts, but in very low yields with only slight asymmetric induction. For allylic alcohol (**8**), the Ni(II)-complex catalyzed reaction with diazo diketone **19**, unlike that with diazo compound **1**, did not give the cycloadduct. For 2,3-dihydrofuran (**13**), the reaction with diazo substrate **19** afforded only the *endo*-cycloadduct in high yields—moreover, upon a survey of solvents and temperatures, $CHCl_3$ at 40 or 45 °C was found as optimal reaction conditions affording moderate enantioselectivity (70% ee, entries 8 and 9). In the case of silyketene acetal **15**, its decomposition occurred as the main process under (*R*)-BINIM-4Me-2QN–Ni(II)-catalyzed conditions, to afford the cycloadduct in low yields with little asymmetric induction. Finally, in the cases of

Table 4
Reactions of α,α′-dicarbonyl diazo compounds **19–27** with olefins **2a**, **2c**, and **2f** catalyzed by (*R*)-BINIM–Ni(II) complexes[a]



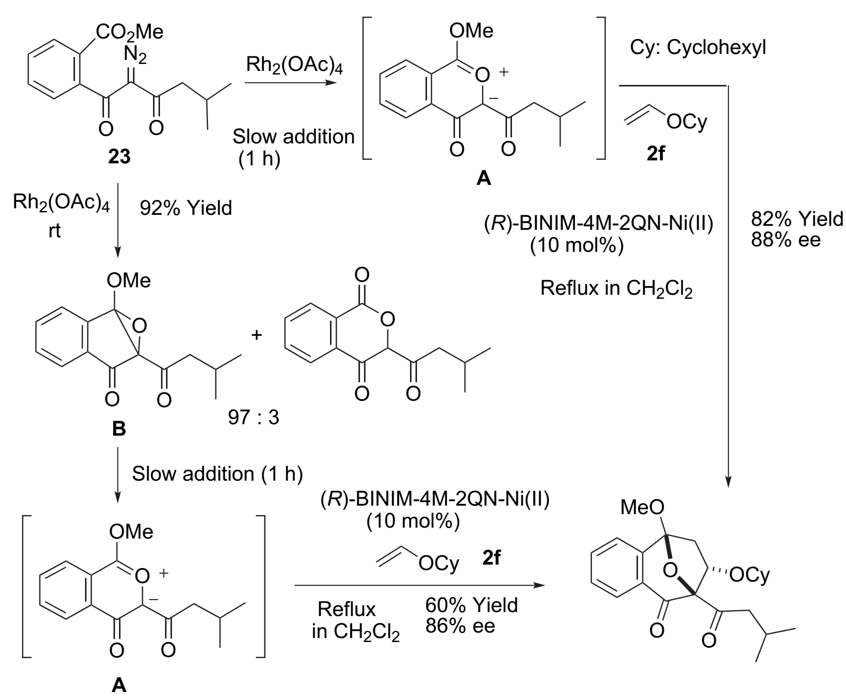
Entry	BINIM ligand	**19–27** (R′)	Olefin	Temp (°C)	Product	Yield (%)	ee[b] (%)
1	2QN	**19** (Pr)	**2a**	rt	**28a**	78	59
2	4(3,5-Xylyl)-2QN	**19** (Pr)	**2a**	rt	**28a**	86	42
3	4Me-2QN	**19** (Pr)	**2a**	rt	**28a**	86	73
4	4Me-2QN	**19** (Pr)	**2a**	Reflux	**28a**	99	92
5	4Me-2QN	**19** (Pr)	**2c**	Reflux	**28c**	76	79
6	4Me-2QN	**19** (Pr)	**2f**	Reflux	**28f**	96	93
7[c]	4Me-2QN	**19** (Pr)	**2f**	Reflux	**28f**	85	90
8[d]	4Me-2QN	**19** (Pr)	**2f**	Reflux	**28f**	80	94
9[e]	4Me-2QN	**19** (Pr)	**2f**	Reflux	**28f**	86	93
10	4Me-2QN	**20** (Et)	**2f**	Reflux	**29f**	77	73
11	4Me-2QN	**21** (*i*-Pr)	**2c**	Reflux	**30c**	85	90
12	4Me-2QN	**21** (*i*-Pr)	**2f**	Reflux	**30f**	96	97
13	4Me-2QN	**22** (Bu)	**2f**	Reflux	**31f**	87	93
14	4Me-2QN	**23** (*i*-Bu)	**2f**	Reflux	**32f**	82	88
15	4Me-2QN	**24** (Pentyl)	**2f**	Reflux	**33f**	66	84
16	4Me-2QN	**25** (Cyclohexyl)	**2f**	Reflux	**34f**	78	96
17	4Me-2QN	**26** (Bn)	**2f**	Reflux	**35f**	85	92
18	4Me-2QN	**27** ($PhCH_2CH_2$)	**2f**	Reflux	**36f**	87	77

[a] The reactions were carried out by adding a solution of **19–27** in CH_2Cl_2 (commercial grade without further purifications) to a suspension of **2a** or **2f**, $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, and BINIM–Ni(II) complexes (10 mol %) over a period of 1 h.
[b] Enantiomeric excess of *endo*-adduct was determined by chiral HPLC.
[c] Dried and purified CH_2Cl_2 by distillation with $CaCl_2$, then CaH_2 was used.
[d] The reaction was carried out in dried and purified CH_2Cl_2 with MeOH (10 mol %) as an additive.
[e] The reaction was carried out by adding a solution of **19** and **2f** over a period of 1 h in dried and purified CH_2Cl_2 with MeOH (10 mol %) as an additive.

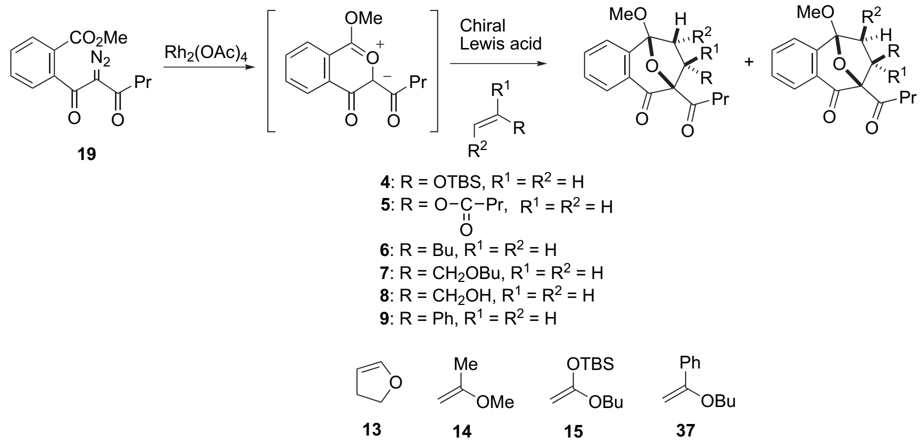
α-substituted vinyl ethers, higher enantioselectivity (44% ee) was obtained in CH_2Cl_2 under reflux conditions for the relatively bulky vinyl ether **37** (entry 12) compared to that of vinyl ether **14** (entry 10).

2.6. Reaction of 1-diazo-2,5-pentandione derivatives with vinyl ethers

To further investigate the scope of our methodology for other diazo compounds, the reaction between diazo diketone **47** and



Scheme 5.



Scheme 6.

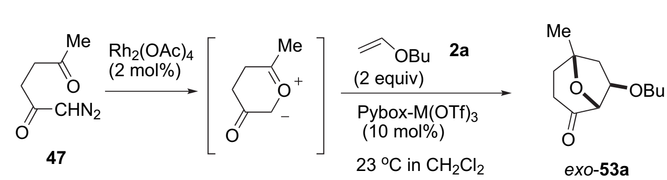
butyl vinyl ether (**2a**) was examined (Scheme 7, Table 6). First, catalysts were prepared from $Eu(OTf)_3$ and three types of Pybox ligands (Fig. 2). Next, to the solutions of these Pybox–Eu(III) complexes, along with vinyl ether **2a** (2 equiv) and $Rh_2(OAc)_4$, in CH_2Cl_2 at 23 °C was added diazo diketone **47** over a period of 1 h (entries 1–3). In contrast to the reaction of 2-benzopyryrium-4-olate generated from *o*-methoycarbonyl-α-diazoacetophenone (**1**), which gave the *endo*-cycloadduct with a high diastereoselectivity, the reactions of diazo diketone **47** selectively formed the *exo*-cycloadduct.[17] Among the three Pybox–Eu(III) complexes, the catalyst involving the (4*S*,5*S*)-Pybox-Ph_2 ligand exhibited the highest enantioselectivity (60% ee, *exo*), which was comparable to that of the reaction with diazoacetophenone **1**. Upon a survey of various lanthanoid metals (Fig. 5, three metals (Eu, Tm, and Lu) are shown in Table 6), catalysts that involve Tm (67% ee) and Lu (77% ee) (entries 4 and 11, respectively) exhibited higher enantioselectivities than those of other lantanoid metals. Maximum *exo*-selectivity (*exo*:*endo*=92:8 (84% de)) was observed for reactions that employ $Gd(OTf)_3$ or $Tb(OTf)_3$ with (4*S*,5*S*)-Pybox-Ph_2 as the ligand (Fig. 5). For the (4*S*,5*S*)-Pybox-Ph_2–Tm(III)-catalyzed reactions (entries 4, 5, 9, and 10), a reaction temperature of 30 °C was found to give the highest enantioselectivity (75% ee). The yield and enantioselectivity were improved by modifying the procedure in which a mixture of diazo diketone **47** and vinyl ether **2a** was added to $Rh_2(OAc)_4$ and the (4*S*,5*S*)-Pybox-Ph_2–Tm(III) complex in CH_2Cl_2 over a period of 1 h (entry 6). In the case of the (4*S*,5*S*)-Pybox-Ph_2–Lu(III)-catalyzed reaction (entry 12), the *exo*-selectivity was also improved by adding a mixture of diazo diketone **47** and vinyl ether **2a**. Again, it is noteworthy that, for the reactions of both $Tm(OTf)_3$ and $Lu(OTf)_3$ (entries 7 and 13, respectively), enantioselectivities were reduced when dried and purified CH_2Cl_2 (via distillation with $CaCl_2$, then CaH_2) was used as the solvent. In the case of the (4*S*,5*S*)-Pybox-Ph_2–Lu(III)-catalyzed reactions, higher enantioselectivities were not obtained by raising the reaction temperature (entries 17 and 18)—the maximum enantioselectivity (78% ee) was observed at 23 °C (entry 12). Finally, the optimal enantioselectivity (82% ee) and *exo*-selectivity (92:8) was achieved using the (4*S*,5*S*)-Pybox-Ph_2–Lu(III) complex in dried and purified CH_2Cl_2 with MeOH (10 mol %) as an additive (entry 14). It is interesting to note that increasing the catalyst loading (20%, entry 15; and 50%, entry 16) resulted in lower enantioselectivities.

Investigations of the R′-substituent of the vinyl ethers (Scheme 8, Table 7, entries 1–6), with the (4*S*,5*S*)-Pybox-Ph_2–Lu(III) complex as the catalyst, demonstrated that the enantioselectivity of butyl vinyl ether (**2a**) was higher than those of *tert*-butyl or cyclohexyl vinyl ethers (**2e** or **2f**, respectively), which was in contrast to the reactions of *o*-methoycarbonyl-α-diazoacetophenone (**1**). Remarkably, TBS vinyl ether (**4**) gave the *exo*-cycloadduct exclusively, in a reasonable yield and with good enantioselectivity (82% ee). To investigate the R-substituent of the diazo compounds (Scheme 8, Table 7, entries 7–11), diazo diketones **48**–**52** were reacted with vinyl ether **2a** in the presence of (4*S*,5*S*)-Pybox-Ph_2–Lu(III) complex to afford the corresponding cycloadducts with good enantioselectivities (75–84% ee) and high *exo*-selectivities (92:8 to >99:1).

Table 5
Reactions of diazo compound **19** with olefins **4**–**9**, **13**–**15**, and **37** catalyzed by the (*R*)-BINIM-4Me-2QN–Ni(II) complex[a]

Entry	Olefins	Solvent	Temp (°C)	Product	Yield (%)	dr[b]	ee[c] (%)	
							Major	Minor
1	**4**	CH_2Cl_2[d]	Reflux	**38**	44	>99:1[e]	6	
2[g]	**4**	CH_2Cl_2[d]	Reflux	**38**	68	>99:1[e]	19	
3	**5**	CH_2Cl_2[d]	Reflux	**39**	2	>99:1[e]	1	
4	**6**	CH_2Cl_2[d]	Reflux	**40**	9	>99:1[e]	4	
5	**7**	CH_2Cl_2[d]	Reflux	**41**	1	>99:1[e]	ND[i]	
6	**9**	$CHCl_3$	Reflux	**42**	9	90:10	10[f]	
7[h]	**9**	CH_2Cl_2[d]	Reflux	**42**	38	89:11	7[f]	
8	**13**	$CHCl_3$	40	**43**	95	>99:1[e]	70	
9	**13**	$CHCl_3$	45	**43**	98	>99:1[e]	70	
10	**14**	CH_2Cl_2[d]	Reflux	**44**	85	61:39	30	17
11	**15**	CH_2Cl_2[d]	Reflux	**45**	12	74:26	2	ND[i]
12	**37**	CH_2Cl_2[d]	Reflux	**46**	68	74:26	44	44

[a] The reactions were carried out by adding a solution of **1** to a suspension of olefins **4**–**9**, **13**–**15**, or **37**, $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, and (*R*)-BINIM-4Me-2QN–Ni(II) complex (10 mol %), which was prepared from (*R*)-BINIM-4Me-2QN and $Ni(ClO_4)_2$ $6H_2O$, over a period of 1 h.
[b] Diastereomer ratio.
[c] Enantiomeric excess of adducts was determined by chiral HPLC.
[d] Commercially available CH_2Cl_2 was used without further purifications.
[e] Only the *endo*-adduct was obtained.
[f] Enantiomeric excess of the major diastereomer.
[g] (4*S*,5*S*)-Pybox-Ph_2–$Eu(OTf)_3$ (10 mol %) was used for the chiral Lewis acid.
[h] $Ni(BF_4)_2$ $6H_2O$ was used for the preparation of the (*R*)-BINIM-4Me-2QN–Ni(II) complex.
[i] Not determined.



Scheme 7.

Table 6
Reactions of diazo compound **47** with vinyl ether **2a** catalyzed by the chiral Pybox–M(OTf)$_3$ complexes[a]

Entry	Pybox[b]	M (Å)[c]	Add. Conditions[d]	Solvent	Temp (°C)	Yield (%)	*exo*:*endo*[e]	ee[f] (%)
1	*i*-Pr	Eu (0.947)	A	CH_2Cl_2	23	79	81:19	16
2	Ph	Eu (0.947)	A	CH_2Cl_2	23	68	84:16	43
3	Ph_2	Eu (0.947)	A	CH_2Cl_2	23	63	84:16	60
4	Ph_2	Tm (0.880)	A	CH_2Cl_2	23	68	88:12	67
5	Ph_2	Tm (0.880)	A	CH_2Cl_2	30	60	91:9	75
6	Ph_2	Tm (0.880)	B	CH_2Cl_2	30	71	91:9	76
7	Ph_2	Tm (0.880)	B	CH_2Cl_2[g]	30	70	90:10	65
8	Ph_2	Tm (0.880)	B	Toluene[k]	30	68	95:5	68
9	Ph_2	Tm (0.880)	A	CH_2Cl_2	35	55	90:10	68
10	Ph_2	Tm (0.880)	A	CH_2Cl_2	Reflux	65	86:14	53
11	Ph_2	Lu (0.861)	A	CH_2Cl_2	23	57	86:14	77
12	Ph_2	Lu (0.861)	B	CH_2Cl_2	23	68	89:11	78
13	Ph_2	Lu (0.861)	B	CH_2Cl_2[g]	23	70	90:10	65
14	Ph_2	Lu (0.861)	B	CH_2Cl_2[h]	23	64	92:8	82
15[i]	Ph_2	Lu (0.861)	B	CH_2Cl_2[h]	23	53	90:10	75
16[j]	Ph_2	Lu (0.861)	B	CH_2Cl_2[h]	23	62	94:16	64
17	Ph_2	Lu (0.861)	B	CH_2Cl_2	30	63	87:13	73
18	Ph_2	Lu (0.861)	B	CH_2Cl_2	35	64	89:11	72

[a] The reactions were carried out by adding a solution of the substrates in CH_2Cl_2 (commercial grade without further purifications) to a suspension of $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, and Pybox–M(OTf)$_3$ complexes (10 mol %) over a period of 1 h.
[b] Ph_2: (4*S*,5*S*)-Pybox-Ph_2, *i*-Pr: (*S*,*S*)-Pybox-*i*-Pr, Ph: (*S*,*S*)-Pybox-Ph.
[c] Ionic radius.
[d] A: The reaction was carried out by adding a solution of **47** to a suspension of **2a**, the catalyst, and MS 4 Å over a period of 1 h. B: The reaction was carried out by adding a solution of **47** and **2a** to a suspension of the catalyst and MS 4 Å over a period of 1 h.
[e] Determined by ^{1}H NMR.
[f] Enantiomeric excess of the *exo*-adduct was determined by ^{1}H NMR after conversion to the corresponding acetal in the reaction with (*R*,*R*)-hydrobenzoin.
[g] Dried and purified CH_2Cl_2 (via distillation with $CaCl_2$, then CaH) was used.
[h] The reaction was carried out in dried and purified CH_2Cl_2 with MeOH (10 mol %) as an additive.
[i] 20 mol % catalyst was used.
[j] 50 mol % catalyst was used.
[k] Dried and purified toluene (typical procedures) was used.

2.7. Reaction of 1-diazo-2,5-hexandione with other electron-rich dipolarophiles

Reactions between diazo substrate **47** and other electron-rich dipolarophiles were evaluated under similar conditions using the (4*S*,5*S*)-Pybox-Ph_2–Lu(OTf)$_3$ complex as the catalyst (Scheme 9, Table 8). Although the reactions of α-substituted vinyl ethers **14** and **15** exhibited slight asymmetric inductions (entry 1 and 2, respectively), the reaction with styrene (**9**) afforded the *endo*-cycloadduct exclusively with 80% ee (entry 3), albeit with a yield of merely 3%.

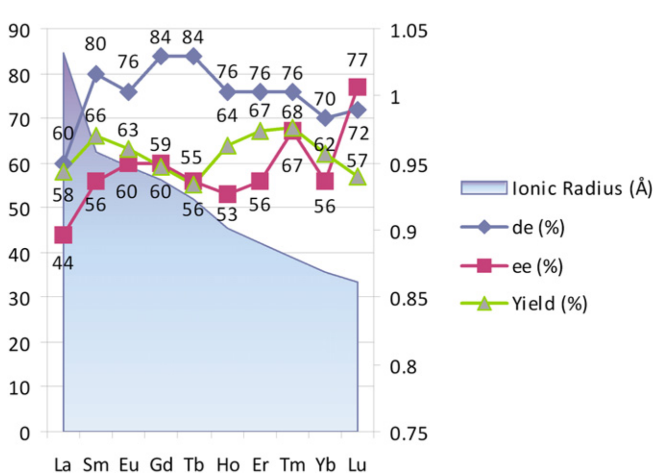


Figure 5. Relationship between the ionic radii and the enantio- and diastereoselectivities and the yields for the reaction of diazo compound **47** with vinyl ether **2a** catalyzed by the chiral (4*S*,5*S*)-Pybox-4,5-Ph_2–M(OTf)$_3$ complexes.

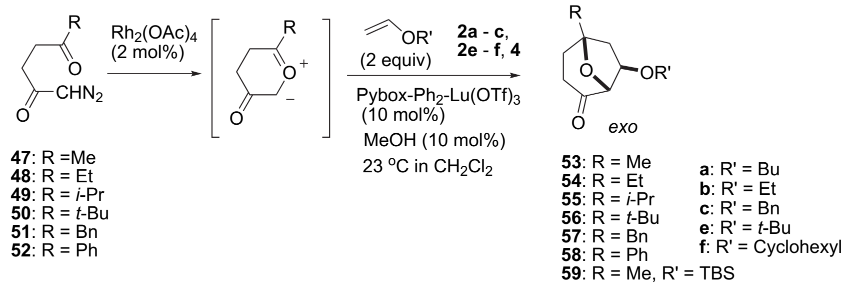
2.8. Absolute configuration of cycloadduct *exo*-53f

Cycloadduct *exo*-**53f** was converted to the corresponding acetal via reaction with (*R*,*R*)-hydrobenzoin in the presence of PPTS in toluene under reflux conditions using a Dean–Stark trap (Scheme 10). Recrystallization from hexane gave a single crystal of the acetal (mp 147–148 °C) that consisted of a single diastereomer (>99% de, determined by 400 MHz ^{1}H NMR). Structural analysis of the crystal using X-ray crystallography showed that all the asymmetric carbons of the corresponding cycloadduct *exo*-**53f** possess the (*R*)-configuration (Fig. 6). These results suggests that the coordination between the (4*S*,5*S*)-Pybox-Ph_2–Lu(OTf)$_3$ complex and the carbonyl ylide effectively shields the approach of vinyl ether **2f** from the upper side, and hence, the formation of cycloadduct *exo*-**53f**, with (*R*)-configurations at all three stereocenters (Fig. 7), involves an approach of vinyl ether **2f** from the lower side with an *exo*-orientation.

Previously, X-ray analysis of the (4*S*,5*S*)-Pybox-Ph_2–La(OTf)$_3$ complex has shown that the La metal possesses nine coordination sites and includes four hydrates.[18] Moreover, the number of the coordination sites may vary according to the type of the lanthanoid metal. Because the Pybox–lantanoid triflate complexes could possess multi-coordination sites, the exact arrangement of the carbonyl ylide coordinated to the Pybox–lanthanoid complexes that shields the upper side could not be easily estimated at this point. However, a similar facial shielding behavior would also explain the efficient asymmetric induction of the reactions between 2-benzopyrylium-4-olate and vinyl ethers.

3. Conclusion

We have successfully developed the inverse-electron-demand dipole-LUMO/dipolarophile-HOMO-controlled cycloaddition reactions of cyclohexyl or butyl vinyl ethers toward carbonyl



Scheme 8.

Table 7

Reactions of diazo compounds **47**–**52** with vinyl ethers **2a**–**c**, **2e** and **2f**, and **4** catalyzed by the (4*S*,5*S*)-Pybox-Ph_2–Lu$(OTf)_3$ complex[a]

Entry	R (Diazo substrates)	R′ (Olefins)	Products	Yield (%)	*exo*:*endo*[b]	ee[c] (%)
1	Me (**47**)	Bu (**2a**)	**53a**	64	92:8	82
2	Me (**47**)	Et (**2b**)	**53b**	52	>99:1	71
3	Me (**47**)	Bn (**2c**)	**53c**	59	95:5	60
4	Me (**47**)	*t*-Bu (**2e**)	**53e**	56	95:5	74[d]
5	Me (**47**)	Cyclohexyl (**2f**)	**53f**	82	89:11	73
6	Me (**47**)	TBS (**4**)	**59**	54	>99:1	82[d]
7	Et (**48**)	Bu (**2a**)	**54a**	61	>99:1	79
8	*i*-Pr (**49**)	Bu (**2a**)	**55a**	76	>99:1	84
9	*t*-Bu (**50**)	Bu (**2a**)	**56a**	73	>99:1	82
10	Bn (**51**)	Bu (**2a**)	**57a**	71	92:8	75[e]
11	Ph (**52**)	Bu (**2a**)	**58a**	75	>99:1	78[e]

[a] The reactions were carried out by adding a solution of diazo compounds **47**–**52** and vinyl ethers **2a**–**c**, **2e** and **2f**, or **4** to a suspension of $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, (4*S*,5*S*)-Pybox-Ph_2–Lu$(OTf)_3$ complex (10 mol %), and MeOH (10 mol %) over a period of 1 h in dried and purified CH_2Cl_2 at 23 °C.

[b] Determined by ^{1}H NMR.

[c] Enantiomeric excess of the *exo*-adduct was determined by ^{1}H NMR after conversion to the corresponding acetal in the reaction with (*R*,*R*)-hydrobenzoin.

[d] Determined by ^{1}H NMR after stereoselective reduction by $NaBH_4$, followed by conversion to the corresponding (*R*)-α-methoxyphenylacetate ester.

[e] Determined by chiral HPLC.

Table 8

Reactions of diazo compound **47** with olefins **14**, **15**, and **9** catalyzed by the (4*S*,5*S*)-Pybox-Ph_2–Lu$(OTf)_3$ complexes[a]

Enrty	Olefins	Products	Yield (%)	dr[b]	ee[c] (%)
1	**14**	**60**	27	81:19[d]	22
2	**15**	**61**	61	63:37[d]	ND[e]
3	**9**	**62**	3	>99:1[f]	80[g]

[a] The reactions were carried out by adding a solution of diazo compound **47** and olefins **14**, **15**, or **9** to a suspension of $Rh_2(OAc)_4$ (2 mol %), MS 4 Å, (4*S*,5*S*)-Pybox-Ph_2–Lu$(OTf)_3$ complex (10 mol %), and MeOH (10 mol %) over a period of 1 h in dried and purified CH_2Cl_2 at 23 °C.

[b] Diastereoselectivity was determined by ^{1}H NMR.

[c] Enantiomeric excess of the major diastereomer was determined by ^{1}H NMR after conversion to the corresponding acetal in the reaction with (*R*,*R*)-hydrobenzoin.

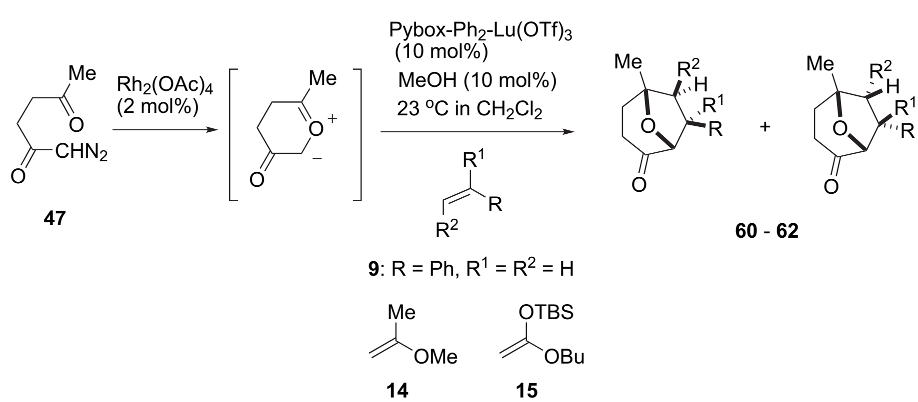
[d] Major/Minor.

[e] Not determined. $[\alpha]_D^{25}$ +2.75 ($CHCl_3$, *c* 1.0) (Major/Minor=63:37).

[f] Only the *exo*-isomer was obtained.

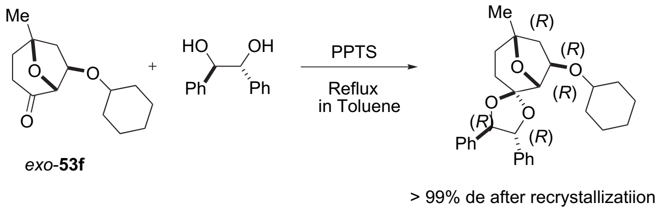
[g] Determined by chiral HPLC.

ylides that were generated from *o*-methoxycarbonyl-α-diazoacetophenone (**1**) or acyl derivatives **19**–**27** via $Rh_2(OAc)_4$-catalyzed decomposition. High levels of asymmetric induction (73–97% ee) were achieved using chiral Pybox–lanthanoid exhibited moderate enanantioselectivities (60–73% ee). The reaction between methyl 2-(2-diazo-1,3-dioxohexyl)benzoate (**19**) and **13** using a BINIM–Ni(II) complex as the chiral Lewis acid also gave the cycloadduct with high *exo*-selectivity and moderate enantioselectivity (70% ee). During studies of the BINIM–Ni(II)-catalyzed reaction between cyclohexyl vinyl ether and an epoxyindanone (as the carbonyl ylide precursor), the chiral Lewis acid



Scheme 9.

metal(III) or BINIM–Ni(II) complexes as the chiral Lewis acid catalysts. The Pybox–lanthanoid metal(III)-catalyzed reactions between *o*-methoxycarbonyl-α-diazoacetophenone (**1**) and electron-rich dipolarophiles such as allyl alcohol (**8**), 2,3-dihydrofuran (**13**), and butyl-*tert*-butyldimethylsilylketene acetal (**15**) without the participation of $Rh_2(OAc)_4$ was found to be an effective catalyst for asymmetric inductions. For the Pybox–lanthanoid metal(III)-catalyzed reaction with butyl vinyl ether, the scope of diazo substrates was extended to include several 1-diazo-2,5-pentanedione derivatives (**47**–**52**) with good levels of



Scheme 10.

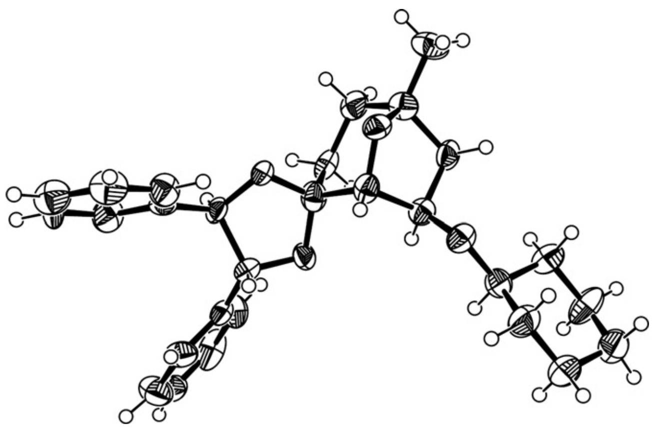


Figure 6. ORTEP drawing of the acetal prepared from *exo*-**53f** and (*R*,*R*)-hydrobenzoin.

4.2. Materials

o-Methoxycarbonyl-α-diazoacetophenone (**1**) was prepared by the procedure in the previous paper.[20] α,α′-Dicarbonyl diazo substrates **19**–**27**[4] and 1-diazo-2,5-alkanedione **47**–**52**[2,21] were prepared according to the procedure reported by Padwa. Ethyl vinyl ether, butyl vinyl ether, *tert*-butyl vinyl ether, cyclohexyl vinyl ether, vinyl butyrate, 2,3-dihydrofuran, allyl alcohol, 1-hexene, styrene, 2-methoxypropene and, $Rh_2(OAc)_4$ were commercially available, and used without further purification. Lanthanoid triflates were commercially available, and dried in vacuo at 200 °C for 12 h before use. *tert*-Butyldimethylsilyl vinyl ether,[22] allyl vinyl ether,[23] 1-(*tert*-butyldimethylsilyloxy)-1-butyloxyethylene,[24] α-butoxystyrene,[25] and 2,6-Bis(oxazolinyl)pyridines[18,26] (Pybox) were prepared by the procedure in the literatures. Powdered 4 Å molecular sieves (MS 4 Å) was commercially available (Aldrich) and dried in vacuo at 200 °C for 12 h before use. $Ni(ClO_4)_2\cdot 6H_2O$ and $Ni(BF_4)_2\cdot 6H_2O$ were commercially available, and used without further purification. Chiral Binaphthyldiimine (BINIM) ligands were prepared by the procedure reported previously.[16] Dichloromethane was commercially available, and used without further purification. For purified dichloromethane, purification was carried out by distillation first from $CaCl_2$ and then CaH_2 under argon before used. Toluene, benzene, THF, and 1,4-dioxane were distilled from a sodium benzophenone ketyl still under argon. Chloroform was purified by distillation first from $CaCl_2$ and then P_2O_5 under argon before used.

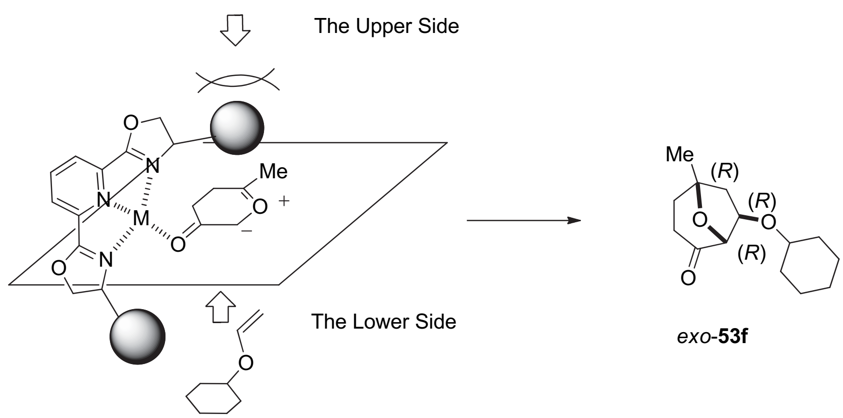


Figure 7. Proposed approaches for asymmetric induction based on the absolute configuration of *exo*-**53f**.

asymmetric induction (75–84% ee). Studies to expand our methodology to other diazo substrates, while optimizing reaction conditions to achieve high enantioselectivities are currently underway.

4. Experimental

4.1. General

Melting points were determined on a melting point apparatus and are uncorrected. IR spectra were taken with a FTIR spectrophotometer. ^1H NMR spectra were recorded on a 400 MHz spectrometer. Chemical shifts are expressed in parts per million downfield from tetramethylsilane as an internal standard. ^{13}C NMR spectra were recorded on a 100 MHz spectrometer using broadband proton decoupling. Chemical shifts are expressed in parts per million using the middle resonance of $CDCl_3$ (77.0 ppm) as an internal standard. For preparative column chromatography, Wakogel C-300HG was employed. All reactions were carried out under an argon atmosphere in dried glassware.

4.3. General procedure for the reaction of *o*-methoxycarbonyl-α-diazoacetophenone (1) with olefins was exemplified the reaction with cyclohexyl vinyl ether (2f) catalyzed by (4*S*,5*S*)-Pybox-Ph$_2$–Eu(III) complex

A solution of 2,6-bis[(4*S*,5*S*)-4,5-diphenyl-2-oxazolin-2-yl]pyridine ((4*S*,5*S*)-Pybox-Ph$_2$, 26.1 mg, 0.05 mmol) in THF (1.5 mL) was added to a solution of $Eu(OTf)_3$ (29.9 mg, 0.05 mmol) in THF (1 mL). After stirring the mixture for 2 h, the solvent was removed under reduced pressure and resulting solid was dried in vacuo at room temperature for 5 h. A solution of Eu(III)–Pybox complex in CH_2Cl_2 (3 mL, commercial grade without further purifications) was transferred to a two-necked round-bottomed flask (30 mL) equipped with reflux condenser. After added MS 4 Å (0.5 g), cyclohexyl vinyl ether (**2f**) (126 mg, 1.00 mmol), $Rh_2(OAc)_4$ (4.4 mg, 0.01 mmol), and CH_2Cl_2 (1 mL, without purification), successively, a solution of diazoacetophenone **1** (102 mg, 0.50 mmol) in CH_2Cl_2 (5 mL, without purification) was added over a period of 1 h using a syringe pump under reflux (bath temp 55 °C). The syringe was washed with CH_2Cl_2 (1 mL, without purification). After removal of MS 4 Å through Celite, the reaction mixture was filtered through a plug of silica gel (3 cm) with AcOEt/hexane (1:1, 80 mL) as an eluent. The solvent was removed in vacuo, and the residue was purified by column chromatography (99:1 hexane/AcOEt) to provide a quantitative amount (quant) of *endo*-**3f** and *exo*-**3f**.

*4.3.1. 7-endo-Butoxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**3a**).* Colorless viscous oil; $[\alpha]_D^{25}$ −77.4 (*c* 1.00, $CHCl_3$) (*endo*:*exo*=81:19, 85% ee (*endo*), 62% ee (*exo*)), IR (neat) 3031, 3009, 2961, 2874, 1707, 1603, 1458, 1300, 1267, 1163, 1113, 1055, 1005 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.79 (3H, t, *J*=7.3 Hz), 1.15 (2H, sext, *J*=7.3 Hz), 1.35 (2H, quint, *J*=7.3 Hz), 2.02 (1H, dd, *J*=13.4, 2.7 Hz), 2.60 (1H, dd, *J*=13.4, 9.8 Hz), 3.27–3.34 (1H, m), 3.45–3.52 (1H, m), 3.46 (3H, s), 4.53 (1H, ddd, *J*=2.7, 9.8, 7.1 Hz), 4.96 (1H, d, *J*=7.1 Hz), 7.42–7.48 (2H, m), 7.58–7.64 (1H, m), 7.99–8.04 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.9 (CH_3), 19.2 (CH_2), 31.6 (CH_2), 42.0 (CH_2), 51.9 (CH_3), 70.7 (CH_2), 76.6 (CH), 83.8 (CH), 106.4 (C), 122.8 (CH), 126.4 (CH), 128.3 (CH), 131.0 (C), 133.6 (CH), 145.1 (C), 192.5 (C); MS (EI) *m*/*z* 276 (M^+), 247, 203, 176, 161, 147, 133, 117, 103, 91, 77, 61, 50, 37, 26, 13; HRMS (EI) calcd for $C_{16}H_{20}O_4$ (M^+): 276.1360. Found: 276.1387. Anal. Calcd for $C_{16}H_{20}O_4$: C, 69.54; H, 7.30%. Found: C, 69.14; H, 7.70%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=22.9 min (minor), 45.7 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^1H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.1 Hz, *exo*:0 Hz).[19] The *endo*/*exo* ratio was determined by ^1H NMR analysis (*endo*:*exo*=81:19) on the basis of the integration corresponding to one of the methylene protons at 6 position.

*4.3.2. 7-exo-Butoxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (exo-**3a**).* Although *exo*-**3a** could not be separated by chromatography from a mixture with major *endo*-**3a**, it could characterize by ^1H and ^{13}C NMR. ^1H NMR ($CDCl_3$) δ 0.93 (3H, t, *J*=7.3 Hz), 1.31–1.45 (2H, m), 1.55–1.66 (2H, m), 2.31 (1H, dd, *J*=13.2, 3.9 Hz), 2.39 (1H, dd, *J*=13.2, 7.3 Hz), 3.37–3.59 (2H, m), 3.55 (3H, s), 3.97 (1H, dd, *J*=3.9, 7.3 Hz), 4.78 (1H, s), 7.42–7.48 (2H, m), 7.58–7.64 (1H, m), 7.93–7.97 (1H, m); ^{13}C NMR ($CDCl_3$) δ 14.0 (CH_3), 19.4 (CH_2), 29.7 (CH_2), 31.7 (CH_2), 51.9 (CH_3), 69.7 (CH_2), 79.8 (CH), 86.5 (CH), 107.4 (C), 122.8 (CH), 126.7 (CH), 128.5 (CH), 129.2 (C), 134.3 (CH), 145.6 (C), 193.5 (C). The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=39.6 min (minor), 36.4 min (major).

*4.3.3. 7-endo-Ethoxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**3b**).* Colorless viscous oil; $[\alpha]_D^{25}$ −95.1 (*c* 1.00, $CHCl_3$) (*endo*:*exo*=83:17, 83% ee (*endo*), 67% ee (*exo*)); IR (neat) 3012, 2980, 1707, 1603, 1458, 1445, 1300, 1267, 1252, 1215, 1165, 1115, 1053, 1005 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.02 (3H, t, *J*=7.1 Hz), 2.02 (1H, dd, *J*=13.2, 2.7 Hz), 2.63 (1H, dd, *J*=13.2, 10.0 Hz), 3.36–3.58 (2H, m), 3.47 (3H, s), 4.55 (1H, ddd, *J*=2.7, 10.0, 7.3 Hz), 4.97 (1H, d, *J*=7.3 Hz), 7.42–7.49 (2H, m), 7.58–7.64 (1H, m), 7.99–8.06 (1H, m); ^{13}C NMR ($CDCl_3$) δ 15.0 (CH_3), 42.1 (CH_2), 51.9 (CH_3), 66.3 (CH_2), 76.4 (CH), 83.8 (CH), 106.4 (C), 122.8 (CH), 126.6 (CH), 128.4 (CH), 130.9 (C), 133.7 (CH), 145.2 (C), 192.7 (C); MS (EI) *m*/*z* 248 (M^+), 216, 203, 176, 161, 147, 133, 129, 115, 103, 89, 76, 61, 47, 39, 26, 13; HRMS (EI) calcd for $C_{14}H_{16}O_4$ (M^+): 248.1048. Found: 248.1050. Anal. Calcd for $C_{14}H_{16}O_4$: C, 67.73; H, 6.50%. Found: C, 67.30; H, 6.62%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=23.5 min (minor), 46.9 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^1H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.3 Hz, *exo*:0 Hz).[19] The *endo*/*exo* ratio was determined by ^1H NMR analysis (*endo*:*exo*=83:17) on the basis of the integration corresponding to one of the methylene protons at 6 position.

*4.3.4. 7-exo-Ethoxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (exo-**3b**).* Although *exo*-**3b** could not be separated by chromatography from a mixture with major *endo*-**3b**, it could characterize by ^1H and ^{13}C NMR. ^1H NMR ($CDCl_3$) δ 1.25 (3H, t, *J*=7.1 Hz), 2.32 (1H, dd, *J*=13.2, 3.7 Hz), 2.41 (1H, dd, *J*=13.2, 7.3 Hz), 3.35–3.60 (2H, m), 3.98 (1H, dd, *J*=3.7, 7.3 Hz), 4.79 (1H, s), 7.42–7.49 (2H, m), 7.58–7.64 (1H, m), 7.93–7.98 (1H, m); ^{13}C NMR ($CDCl_3$) δ 15.3 (CH_3), 42.2 (CH_2), 52.0 (CH_3), 65.4 (CH_2), 79.7 (CH), 86.6 (CH), 107.4 (C), 122.9 (CH), 126.8 (CH), 128.6 (CH), 129.3 (C), 134.3 (CH), 145.6 (C), 193.5 (C). The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=32.3 min (major), 42.6 min (minor).

*4.3.5. 7-endo-Benzyloxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**3c**).* Colorless viscous oil; $[\alpha]_D^{25}$ −46.0 (*c* 0.44, $CHCl_3$) (*endo*:*exo*=80:20, 61% ee (*endo*), ND (*exo*)); IR (neat) 3012, 2947, 1705, 1601, 1454, 1400, 1300, 1153, 1092, 1053, 945, 891, 833 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.07 (1H, dd, *J*=2.9, 13.4 Hz), 2.61 (1H, dd, *J*=9.8, 13.4 Hz), 3.46 (3H, s), 4.38 (1H, d, *J*=11.5 Hz), 4.58 (1H, d, *J*=11.5 Hz), 4.65 (1H, ddd, *J*=2.9, 7.1, 9.8 Hz), 5.02 (1H, d, *J*=7.1 Hz), 7.16–7.30 (5H, m), 7.44–7.48 (2H, m), 7.59–7.63 (1H, m), 8.05–8.07 (1H, m); ^{13}C NMR ($CDCl_3$) δ 41.9 (CH_2), 51.9 (CH_3), 72.4 (CH_2), 75.8 (CH), 83.6 (CH), 106.4 (C), 122.9 (CH), 126.6 (CH), 127.6 (CH), 128.2 (CH), 128.5 (CH), 130.9 (C), 133.8 (CH), 137.0 (C), 145.2 (C), 192.7 (C); MS (EI) *m*/*z* 310 (M^+), 281, 267, 250, 237, 219, 201, 190, 173, 161, 145, 131, 115, 103, 91, 77, 65, 50, 39, 27, 15, 3; HRMS (EI) calcd for $C_{19}H_{18}O_4$ (M^+): 310.1205. Found: 310.1221. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=51.5 min (minor), 106.8 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^1H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.1 Hz, *exo*:0 Hz).[19] The *endo*/*exo* ratio was determined by ^1H NMR analysis (*endo*:*exo*=80:20) on the basis of the integration corresponding to one of the methylene protons at 6 position.

*4.3.6. 7-exo-Benzyloxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (exo-**3c**).* Although *exo*-**3c** could not be separated by chromatography from a mixture with major *endo*-**3c**, it could characterize by ^1H NMR. ^1H NMR ($CDCl_3$) δ 2.35–2.44 (2H, m), 3.56 (3H, s), 4.09 (1H, dd, *J*=4.4, 6.6 Hz), 4.51 (1H, d, *J*=12.0 Hz), 4.66 (1H, d, *J*=12.0 Hz), 4.88 (1H, s), 7.16–7.32 (5H, m), 7.34–7.35 (3H, m), 7.93–7.95 (1H, m).

*4.3.7. 5-Methoxy-7-endo-(p-methoxybenzyloxy)-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**3d**).* Colorless viscous oil; $[\alpha]_D^{25}$ −45.1 (*c* 0.50, $CHCl_3$) (*endo*:*exo*=82:18, 79% ee (*endo*), 55% ee (*exo*)); IR (neat) 3008, 2951, 2846, 1705, 1608, 1516, 1458, 1296, 1250, 1173, 1045, 883 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.04 (1H, dd, *J*=2.9, 13.4 Hz), 2.59 (1H, dd, *J*=10.0, 13.4 Hz), 3.46 (3H, s), 3.76 (3H, s), 4.31 (1H, d, *J*=11.2 Hz), 4.51 (1H, d, *J*=11.2 Hz), 4.63 (1H, ddd, *J*=2.9, 10.0, 7.3 Hz), 5.01 (1H, d, *J*=7.3 Hz), 6.79–6.83 (2H, m), 7.10–7.12 (2H, m), 7.42–7.46 (2H, m), 7.58–7.62 (1H, m), 8.05–8.07 (1H, m); ^{13}C NMR ($CDCl_3$) δ 41.9 (CH_2), 51.9 (CH_3), 55.3 (CH_3), 72.1 (CH_2), 75.4 (CH), 83.7 (CH), 106.4 (C), 113.7 (CH), 122.9 (CH), 126.6 (CH), 128.4 (CH), 129.1 (C), 129.4 (CH), 130.9 (C), 133.8 (CH), 145.2 (C), 159.1 (C), 192.7 (C); MS (EI) *m*/*z* 340 (M^+), 308, 204, 187, 176, 161, 147, 133, 122, 103, 91, 77, 65, 50, 39, 27, 15, 3. Anal. Calcd for $C_{20}H_{20}O_5$: C, 70.57; H, 5.92%. Found: C, 70.48; H, 6.00%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak OD-3, 1:24 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=25.2 min (minor), 35.6 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.3 Hz, *exo*:0 Hz).[19] The *endo*/*exo* ratio was determined by ^{1}H NMR analysis (*endo*:*exo*=82:18) on the basis of the integration corresponding to one of the methylene protons at 6 position.

*4.3.8. 5-Methoxy-7-exo-(p-methoxybenzyloxy)-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (exo-**3d**).* Although *exo*-**3d** could not be separated by chromatography from a mixture with major *endo*-**3d**, it could characterize by ^{1}H and ^{13}C NMR. ^{1}H NMR ($CDCl_3$) δ 2.37 (2H, m), 3.55 (3H, s), 3.79 (3H, s), 4.07 (1H, dd, *J*=4.6, 6.3 Hz), 4.44 (1H, d, *J*=11.5 Hz), 4.59 (1H, d, *J*=11.5 Hz), 4.86 (1H, s), 6.86–6.88 (2H, m), 7.26–7.28 (2H, m), 7.42–7.62 (3H, m), 7.93–7.95 (1H, m); ^{13}C NMR ($CDCl_3$) δ 42.0 (CH_2), 52.0 (CH_3), 55.3 (CH_3), 72.1 (CH_2), 75.5 (CH), 78.7 (CH), 106.7 (C), 113.8 (CH), 123.0 (CH), 126.8 (CH), 128.6 (CH), 129.0 (C), 129.4 (CH), 130.9 (C), 134.3 (CH), 145.6 (C), 159.5 (C), 192.8 (C). The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak OD-3, 1:24 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=28.4 min (minor), 31.0 min (major).

*4.3.9. 7-endo-tert-Butoxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**3e**).* Colorless viscous oil; $[\alpha]_D^{25}$ −112.8 (*c* 1.00, $CHCl_3$) (***endo*:*exo*=87:13, 88% ee (*endo*), 74% ee (*exo*)**); IR (neat) 3021, 2978, 1709, 1603, 1458, 1393, 1368, 1298, 1267, 1215, 1150, 1078, 1051, 1028, 1007 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.09 (9H, s), 1.92 (1H, dd, *J*=13.2, 2.7 Hz), 2.61 (1H, dd, *J*=13.2, 9.8 Hz), 3.46 (3H, s), 4.69 (1H, ddd, *J*=2.7, 9.8, 7.6 Hz), 4.77 (1H, d, *J*=7.6 Hz), 7.36–7.51 (2H, m), 7.50–7.67 (1H, m), 7.98–8.04 (1H, m); ^{13}C NMR ($CDCl_3$) δ 28.0 ($CH_3\times3$), 44.1 (CH_2), 51.8 (CH_3), 69.2 (CH), 74.5 (C), 84.9 (CH), 106.5 (C), 122.8 (CH), 126.5 (CH), 128.2 (CH), 131.2 (C), 133.4 (CH), 145.2 (C), 192.6 (C); MS (EI) *m*/*z* 276 (M^+), 261, 221, 203, 179, 160, 145, 129, 115, 103, 91, 76, 57, 49, 39, 26, 13. Anal. Calcd for $C_{16}H_{20}O_4$: C, 69.54; H, 7.30%. Found: C, 69.44; H, 7.38%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=27.5 min (minor), 64.1 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.6 Hz, *exo*:0 Hz).[19] The *endo*/*exo* ratio was determined by ^{1}H NMR analysis (*endo*:*exo*=87:13) on the basis of the integration corresponding to one of the methylene protons at 6 position.

*4.3.10. 7-exo-tert-Butoxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (exo-**3e**).* Although *exo*-**3e** could not be separated by chromatography from a mixture with major *endo*-**3e**, it could characterize by ^{1}H and ^{13}C NMR. ^{1}H NMR ($CDCl_3$) δ 1.21 (9H, s), 2.28 (1H, dd, *J*=13.2, 4.2 Hz), 2.39 (1H, dd, *J*=13.2, 7.6 Hz), 3.54 (3H, s), 4.18 (1H, dd, *J*=4.2, 7.6 Hz) 4.67 (1H, s), 7.36–7.51 (2H, m), 7.50–7.67 (1H, m), 7.94–7.98 (1H, m); ^{13}C NMR ($CDCl_3$) δ 28.3 ($CH_3\times3$), 44.1 (CH_2), 52.1 (CH_3), 72.5 (CH), 74.9 (C), 89.7 (CH), 107.5 (C), 123.0 (CH), 126.8 (CH), 128.5 (CH), 129.3 (C), 134.2 (CH), 145.5 (C), 193.5 (C). The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=22.5 min (major), 36.2 min (minor).

*4.3.11. 7-endo-Cyclohexyloxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**3f**).* Colorless viscous oil; $[\alpha]_D^{25}$ −99.9 (*c* 1.00, $CHCl_3$) (*endo*:*exo*=88:12, 95% ee (*endo*), 47% ee (*exo*)); IR (neat) 3021, 2938, 2859, 1707, 1603, 1453, 1300, 1263, 1215, 1161, 1101, 1078, 1053, 1026, 1007 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.00–1.82 (10H, m), 1.99 (1H, dd, *J*=13.2, 2.7 Hz), 2.61 (1H, dd, *J*=13.2, 9.8 Hz), 3.22–3.32 (1H, m), 3.50 (3H, s), 4.71 (1H, ddd, *J*=2.7, 9.8, 7.3 Hz,), 4.91 (1H, d, *J*=7.3 Hz), 7.40–7.49 (2H, m), 7.57–7.64 (1H, m), 7.98–8.04 (1H, m); ^{13}C NMR ($CDCl_3$) δ 24.0 (CH_2), 24.1 (CH_2), 25.7 (CH_2), 31.7 (CH_2), 32.4 (CH_2), 42.7 (CH_2), 51.8 (CH_3), 73.5 (CH), 77.6 (CH), 84.0 (CH), 106.4 (C), 122.8 (CH), 126.4 (CH), 128.3 (CH), 131.1 (C), 133.5 (CH), 145.1 (C), 192.8 (C); MS (EI) m/z 302 (M^+), 220, 204, 176, 161, 143, 133, 115, 103, 91, 77, 67, 55, 47, 37, 24, 16. Anal. Calcd for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33%. Found: C, 71.58; H, 7.60%. The enantiomeric excess (*endo*) was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=29.4 min (minor), 71.1 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.3 Hz, *exo*:0 Hz).[19] The *endo*/*exo* ratio was determined by ^{1}H NMR analysis (*endo*:*exo*=88:12) on the basis of the integration corresponding to one of the methylene protons at 6 position.

*4.3.12. 7-exo-Cyclohexyloxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (exo-**3f**).* Although *exo*-**3d** could not be separated by chromatography from a mixture with major *endo*-**3f**, it could characterize by ^{1}H and ^{13}C NMR. ^{1}H NMR ($CDCl_3$) δ 1.00–1.82 (10H, m), 2.31 (1H, dd, *J*=13.2, 3.9 Hz), 2.39 (1H, dd, *J*=13.2, 7.3 Hz), 3.32–3.38 (1H, m), 3.55 (3H, s), 4.14 (1H, dd, *J*=3.9, 7.3 Hz), 4.74 (1H, s), 7.40–7.49 (2H, m), 7.57–7.64 (1H, m), 7.93–7.98 (1H, m); ^{13}C NMR ($CDCl_3$) δ 24.1 (CH_2), 24.2 (CH_2), 29.7 (CH_2), 32.0 (CH_2), 32.8 (CH_2), 42.6 (CH_2), 52.0 (CH_3), 76.9 (CH), 77.2 (CH), 87.8 (CH), 107.4 (C), 122.9 (CH), 126.7 (CH), 128.5 (CH), 129.2 (C), 134.2 (CH), 145.5 (C), 193.6 (C). The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=39.6 min (minor), 36.4 min (major).

*4.3.13. 7-endo-(tert-Butyldimethylsilyl)oxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**10**).* Colorless viscous oil; $[\alpha]_D^{25}$ −32.1 (*c* 0.17, $CHCl_3$) (*endo*:*exo*=>99:1, 14% ee (*endo*)); IR (neat) 3413, 3159, 3070, 2939, 2897, 2858, 1716, 1601, 1462, 1396, 1362, 1292, 1257, 1200, 1161, 1107, 1049, 1011, 960, 899 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ −0.05 (3H, s), 0.01 (3H, s), 0.67 (9H, s), 1.91 (1H, dd, *J*=2.0, 12.9 Hz), 2.58 (1H, dd, *J*=8.8, 12.9 Hz), 3.45 (3H, s), 4.81 (1H, d, *J*=7.3 Hz), 4.87 (1H, ddd, *J*=2.0, 8.8, 7.3 Hz), 7.41–7.50 (2H, m), 7.57–7.65 (1H, m), 7.97–8.00 (1H, m); ^{13}C NMR ($CDCl_3$) δ −5.0 (CH_3), −4.9 (CH_3), 17.9 (C), 25.5 (CH_3), 44.9 (CH_2), 51.9 (CH_3), 69.6 (CH), 84.8 (CH), 106.7 (C), 122.9 (CH), 126.3 (CH), 128.3 (CH), 131.5 (C), 133.4 (CH), 144.9 (C), 192.3 (C); MS (EI) *m*/*z* 334 (M^+), 319, 303, 291, 278, 259, 249, 231, 217, 203, 189, 177, 161, 145, 133, 116, 102, 89, 76, 59, 45, 29, 15, 3. Anal. Calcd for $C_{18}H_{26}O_4Si$: C, 64.64; H, 7.83%. Found: C, 64.38; H, 8.01%. The enantiomeric excess (*endo*) was determined by HPLC analysis (DAICEL Chiralpak AD-3, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=14.3 min (minor), 39.9 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.3 Hz).[19]

*4.3.14. 7-endo-Hydroxymethyl-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (endo-**11**).* Colorless viscous oil; $[\alpha]_D^{25}$ +113.2 (*c* 0.65, $CHCl_3$) (*endo*:*exo*=>99:1, 60% ee (*endo*)); IR (neat) 3537, 3032, 2993, 2947, 1697, 1601, 1458, 1392, 1296, 1176, 1065, 972, 864 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.65 (1H, dd, *J*=5.6, 12.9 Hz), 2.49 (1H, dd, *J*=11.2, 12.9 Hz), 3.10–3.20 (1H, m), 3.25 (1H, dd, *J*=9.5, 11.7 Hz), 3.51 (3H, s), 3.51 (1H, dd, *J*=5.9, 11.7 Hz), 4.92 (1H, d, *J*=8.1 Hz), 7.44–7.50 (2H, m), 7.62–7.67 (1H, m), 8.01–8.04 (1H, m); ^{13}C NMR ($CDCl_3$) δ 36.7 (CH_2), 41.3 (CH_2), 52.1 (CH_3), 62.3 (CH), 83.4 (CH), 107.0 (C), 122.7 (CH), 126.7 (CH), 128.5 (CH), 130.2 (C), 134.5 (CH), 146.5 (C), 195.7 (C); MS (EI) *m*/*z* 234 (M^+), 219, 203, 189, 178, 171, 161, 145, 133, 115, 104, 91, 83, 76, 63, 57, 49, 39, 31, 15, 3. Anal. Calcd for $C_{13}H_{14}O_4$: C, 66.66; H, 6.02%. Found: C, 66.48; H, 5.87%. The enantiomeric excess (*endo*) was determined by HPLC analysis (DAICEL Chiralpak OD-3, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=21.0 min (minor), 22.4 min (major). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:8.1 Hz).[19]

*4.3.15. 5-Methoxy-6-phenyl-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (**12**).* Mixture of diastereomers, 69:31; Colorless viscous oil; $[\alpha]_D^{25}$ −7.5 (*c* 0.12, $CHCl_3$) (69:31 Mixture of diastereomers, 10% ee (major), 20% ee (minor)); IR (neat) 2954, 2862, 1782, 1712, 1604, 1462, 1389, 1257, 1084, 1038, 895 cm^{-1}; ^{1}H NMR ($CDCl_3$) Major: δ 2.00 (1H×0.69, ddd, *J*=2.0, 7.6, 14.2 Hz), 3.04 (1H×0.69, ddd, *J*=9.3, 11.2, 14.2 Hz), 3.49 (3H×0.69, s), 3.79 (1H×0.69, dd, *J*=7.6, 11.2 Hz), 4.91 (1H×0.69, dd, *J*=2.0, 9.3 Hz), 6.65–6.71 (2H×0.69, m), 7.04–7.16 (3H×0.69, m), 7.27–8.09 (4H×0.69, m); Minor: δ 2.39 (1H×0.31, ddd, *J*=1.7, 9.3, 14.2 Hz), 2.62 (1H×0.31, ddd, *J*=3.7, 9.3, 14.2 Hz), 3.32 (3H×0.31, s), 3.38 (1H×0.31, dd, *J*=3.7, 9.3 Hz), 4.96 (1H×0.31, dd, *J*=1.7, 9.3 Hz), 6.65–6.71 (3H×0.31, m), 7.04–7.16 (2H×0.31, m), 7.27–8.09 (4H×0.31, m); ^{13}C NMR ($CDCl_3$) Major: δ 31.5 (CH_2), 51.6 (CH_3), 52.7 (CH), 79.5 (CH), 109.3 (C), 125.9 (CH), 126.7 (CH), 126.8 (CH), 127.7 (CH), 127.9 (CH), 128.7 (CH), 130.4 (C), 133.0 (CH), 136.6 (C), 141.2 (C), 194.8 (C); Minor: δ 36.1 (CH_2), 52.3 (CH_3), 53.6 (CH), 78.9 (CH), 108.6 (C), 123.5 (CH), 126.8 (CH), 127.3 (CH), 127.4 (CH), 128.1 (CH), 128.6 (CH), 129.9 (C), 134.2 (CH), 140.9 (C), 145.5 (C), 194.8 (C); MS (EI) *m*/*z* 280 (M$^+$), 248, 219, 191, 163, 133, 105, 77, 50, 28, 3. Anal. Calcd for $C_{18}H_{16}O_3$+H_2O: C, 72.47; H, 6.08%. Found: C, 72.40; H, 6.02%. The enantiomeric excess (major diastereomer) was determined by HPLC analysis (DAICEL Chiralpak AD-3, 1:200 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=44.6 min (minor), 88.7 min (major). The enantiomeric excess (minor diastereomer) was determined by HPLC analysis (DAICEL Chiralpak AD-3, 1:200 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=69.6 min (minor), 117.2 min (major).

*4.3.16. 6-endo-7-endo-5-Methoxy-8-oxabenzo[c]tetrahydrofuro[3,2-f]bicyclo[3.2.1]octan-2-one (endo-**16**).* Colorless viscous oil; $[\alpha]_D^{25}$ −147.1 (*c* 0.26, $CHCl_3$) (59% ee (*endo*)); IR (neat) 2976, 2951, 2890, 2845, 2361, 2340, 1713, 1601, 1456, 1331, 1310, 1290, 1246, 1200, 1169, 1088, 1061, 1044, 1013 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.42–1.52 (1H, m), 1.89–2.02 (1H, m), 2.73 (1H, q, *J*=8.1 Hz), 3.28 (1H, dt, *J*=8.8, 2.4 Hz), 3.45 (3H, s), 3.65 (1H, dt, *J*=8.8, 4.4 Hz), 4.91 (1H, d, *J*=7.3 Hz), 5.15 (1H, dd, *J*=8.1, 7.3 Hz), 7.43–7.54 (2H, m), 7.61–7.68 (1H, m), 8.03–8.08 (1H, m); ^{13}C NMR ($CDCl_3$) δ 26.6 (CH_2), 52.3 (CH_3), 52.9 (CH), 72.0 (CH_2), 83.1 (CH), 83.7 (CH), 108.4 (C), 125.2 (CH), 126.6, (CH), 129.0 (CH), 132.3 (C), 133.1 (CH), 141.2 (C), 192.1 (C); MS (EI) *m*/*z* 246 (M$^+$), 217, 202, 187, 173, 161, 148, 139, 128, 115, 102, 91, 76, 63, 55, 47, 35, 24, 13. Anal. Calcd for $C_{14}H_{14}O_4$: C, 68.28; H, 5.73%. Found: C, 68.28; H, 5.68%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:9 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=17.9 min (major), 18.8 min (minor). Relative stereochemistry (*endo*/*exo*) of the products could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*endo*:7.3 Hz).[19]

*4.3.17. 5,7-Dimethoxy-7-methyl-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (**17**).* Mixture of diastereomer, 47:53 (*endo*/*exo*); Colorless viscous oil; $[\alpha]_D^{25}$ −24.0 (*c* 0.21, $CHCl_3$) (*endo*:*exo*=47:53, 12% ee (*endo*), 15% ee (*exo*)); IR (neat) 3066, 2978, 2835, 1705, 1597, 1454, 1377, 1288, 1149, 1045, 972, 899 cm^{-1}; ^{1}H NMR ($CDCl_3$) *endo*: δ 1.16 (3H×0.47, s), 1.99 (1H×0.47, d, *J*=13.7 Hz), 2.63 (1H×0.47, dd, *J*=1.0, 13.7 Hz), 3.34 (3H×0.47, s), 3.54 (3H×0.47, s), 4.71 (1H×0.47, d, *J*=1.0 Hz), 7.43–7.47 (2H×0.47, m), 7.58–7.64 (1H×0.47, m), 7.97–7.99 (1H×0.47, m); *exo*: δ 1.66 (3H×0.53, s), 2.22 (1H×0.53, d, *J*=13.2 Hz), 2.26 (1H×0.53, d, *J*=13.2 Hz), 3.13 (3H×0.53, s), 3.48 (3H×0.53, s), 4.50 (1H×0.53, s), 7.43–7.47 (2H×0.53, m), 7.58–7.64 (1H×0.53, m), 8.01–8.03 (1H×0.53, m); ^{13}C NMR ($CDCl_3$) *endo*: δ 25.2 (CH_2), 47.9 (CH_2), 51.8 (CH_3), 52.0 (CH_3), 87.7 (CH), 110.0 (C), 111.1 (C), 122.5 (CH), 126.6 (CH), 128.4 (CH), 134.3 (CH), 136.7 (C), 141.7 (C), 177.2 (C); *exo*: δ 20.8 (CH_2), 47.2 (CH_2), 51.0 (CH_3), 52.3 (CH_3), 89.7 (CH), 106.1 (C), 106.2 (C), 122.7 (CH), 126.7 (CH), 128.6 (CH), 133.7 (CH), 135.6 (C), 140.7 (C), 176.9 (C); MS (EI) *m*/*z* 248 (M$^+$), 233, 216, 201, 185, 177, 163, 155, 148, 141, 131, 128, 115, 101, 90, 83, 74, 63, 50, 42, 31, 15. Satisfactory elemental analysis was not obtained. The enantiomeric excess (*endo*) was determined by HPLC analysis (DAICEL Chiralpak AD-3, 1:200 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=17.2 min (minor), 24.6 min (major). The enantiomeric excess (*exo*) was determined by HPLC analysis (DAICEL Chiralpak AD-3, 1:200 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=18.1 min (minor), 19.3 min (major).

*4.3.18. 7-Butoxy-7-(tert-butyldimethylsilyl)oxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]octan-2-one (**18**).* Mixture of diastereomer, 74:26; Pale yellow viscous oil; $[\alpha]_D^{25}$ +21.3 (*c* 1.00, $CHCl_3$) (74:26 Mixture of diastereomer, 72% ee (major), 55% ee (minor)); IR (neat) 2951, 2866, 1709, 1604, 1462, 1392, 1296, 1261, 1134, 1076 cm^{-1}; ^{1}H NMR ($CDCl_3$) Major: δ 0.23 (3H×0.74, s), 0.26 (3H×0.74, s), 0.69 (3H×0.74, t, *J*=7.3 Hz), 0.94 (9H×0.74, s), 1.17–1.25 (2H×0.74, m), 1.36–1.48 (2H×0.74, m), 2.39 (1H×0.74, d, *J*=12.9 Hz), 2.50 (1H×0.74, d, *J*=12.9 Hz), 3.27 (1H×0.74, ddd, *J*=6.8, 9.8, 16.1 Hz), 3.50 (3H×0.74, s), 3.52–3.58 (1H×0.74, m), 4.64 (1H×0.74, s), 7.38–7.45 (2H×0.74, m), 7.52–7.60 (1H×0.74, m), 7.95–7.97 (1H×0.74, m); Minor: δ −0.39 (3H×0.26, s), 0.04 (3H×0.26, s), 0.57 (9H×0.26, s), 0.95 (3H×0.26, t, *J*=7.3 Hz), 1.36–1.65 (4H×0.26, m), 2.26 (1H×0.26, d, *J*=13.2 Hz), 2.65 (1H×0.26, d, *J*=13.2 Hz), 3.50 (3H×0.26, s), 3.52–3.58 (1H×0.26, m), 3.64 (1H×0.26, ddd, *J*=6.3, 7.1, 9.3 Hz), 4.76 (1H×0.26, s), 7.38–7.45 (2H×0.26, m), 7.52–7.60 (1H×0.26, m), 7.95–7.97 (1H×0.26, m); ^{13}C NMR ($CDCl_3$) Major: δ −3.0 (CH_3), 1.2 (CH_3), 13.8 (CH_3), 18.4 (C), 19.0 (CH_2), 25.9 (CH_3), 31.5 (CH_2), 48.0 (CH_2), 51.7 (CH_3), 63.5 (CH_2), 90.4 (CH), 106.2 (C), 106.9 (C), 122.5 (CH), 126.4 (CH), 128.5 (CH), 130.3 (C), 133.5 (CH), 144.5 (C); Minor: δ −4.0 (CH_3), −3.5 (CH_3), 14.1 (CH_3), 18.0 (C), 19.5 (CH_2), 25.3 (CH_3), 32.1 (CH_2), 48.9 (CH_2), 51.7 (CH_3), 63.1 (CH_2), 85.3 (CH), 105.8 (C), 106.4 (C), 122.9 (CH), 126.5 (CH), 128.5 (CH), 130.6 (C), 133.6 (CH), 144.3 (C), 191.0 (C); MS (EI) *m*/*z* 406 (M$^+$), 391, 377, 349, 333, 317, 305, 289, 275, 261, 247, 231, 217, 203, 189, 177, 159, 145, 129, 115, 103, 89, 73, 59, 41, 29, 15, 3. Anal. Calcd for $C_{22}H_{34}O_5Si$: C, 64.99; H, 8.43%. Found: C, 64.88; H, 8.52%. The enantiomeric excess (major) was determined by HPLC analysis (DAICEL Chiralpak OD-3, 1:200 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=7.8 min (major), 13.8 min (minor). The enantiomeric excess (minor) was determined by HPLC analysis (DAICEL Chiralpak OD-3, 1:200 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=9.1 min (minor), 14.5 min (major).

4.4. General procedure for the reactions of α,α′-dicarbonyl diazo compounds 19–27 with olefins was exemplified the reaction of methyl 2-(2-diazo-1,3-dioxohexyl)benzoate (19) with butyl vinyl ether (2a) catalyzed by (*R*)-BINIM-4Me-2QN–Ni(II) complex

A solution of (*R*)-BINIM-4Me-2QN (29.5 mg, 0.05 mmol) in CH_2Cl_2 (2.5 mL, without purification) was added to a mixture of powdered MS 4 Å (500 mg) and $Ni(ClO_4)_2\cdot6H_2O$ (18.3 mg, 0.05 mmol) in a two-necked round-bottomed flask (30 mL) equipped with reflux condenser, and then stirred for 6 h at room temperature. After added butyl vinyl ether (**2a**) (100 mg, 1.00 mmol), $Rh_2(OAc)_4$ (4.4 mg, 0.01 mmol) and CH_2Cl_2 (1.5 mL, without purification), successively, a solution of diazo compound **19** (137 mg, 0.50 mmol) in CH_2Cl_2 (5 mL, without purification) was added over a period of 1 h using a syringe pump under reflux (bath temp 55 °C). The syringe was washed with CH_2Cl_2 (1 mL, without purification). After removal of MS 4 Å through Celite, the reaction mixture was filtered through a plug of silica gel (3 cm) with AcOEt/hexane (1:1, 80 mL) as an eluent. The solvent was removed in vacuo, and the residue was purified by column chromatography

(99:1 hexane/AcOEt) to provide 172 mg (99%) of *endo*-**28a**. Relative stereochmistry (*endo*/*exo*) of the products **28a**, **28c**, **30c**, **28f**–**36f**, **38**–**41**, **43**, and **44** could be determined by ^{1}H NMR analysis on the basis of chemical shifts of H-2 (and a coupling constant between H-1 and H-2) compared with *endo*-**3a**–**f**, *exo*-**3a**–**f**, *endo*-**10**, *endo*-**11**, and *endo*-**16**.

*4.4.1. 1-Butanoyl-7-endo-butoxy-5-methoxy-8-oxabenzo[c]bicyclo-[3.2.1]octan-2-one (endo-**28a**).* Colorless viscous oil; $[\alpha]_D^{25}$ +175.8 (*c* 1.00, $CHCl_3$) (92% ee); IR (neat) 3025, 2963, 2936, 2874, 1730, 1701, 1603, 1458, 1404, 1368, 1302, 1269, 1217, 1171, 1101, 1065, 1040, 1007 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.76 (3H, t, *J*=7.3 Hz), 0.95 (3H, t, *J*=7.3 Hz), 1.09 (2H, sext, *J*=7.3 Hz), 1.20–1.34 (2H, m), 1.61–1.76 (2H, m), 2.08 (1H, dd, *J*=13.2, 1.7 Hz), 2.55 (1H, ddd, *J*=6.6, 8.1, 18.3 Hz), 2.60 (1H, dd, *J*=13.2, 9.5 Hz), 2.73 (1H, ddd, *J*=6.6, 8.1, 18.3 Hz), 3.36 (1H, dt, *J*=6.4, 9.5 Hz), 3.50 (1H, dt, *J*=6.4, 9.5 Hz), 3.50 (3H, s), 4.55 (1H, dd, *J*=1.7, 9.5 Hz), 7.45–7.51 (2H, m), 7.61–7.66 (1H, m), 7.98–8.02 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.7 (CH_3), 13.8 (CH_3),16.5 (CH_2), 19.1 (CH_2), 31.5 (CH_2), 41.2 (CH_2), 43.0 (CH_2), 52.0 (CH_3), 70.5 (CH_2), 77.8 (CH), 95.3 (C), 106.7 (C), 123.1 (CH), 126.5 (CH), 128.6 (CH), 131.2 (C), 133.7 (CH), 144.1 (C), 189.3 (C), 203.5 (C); MS (EI) *m*/*z* 346 (M^+), 303, 246, 231, 186, 175, 161, 147, 129, 117, 103, 91, 71, 61, 49, 39, 26, 13; HRMS (EI) calcd for $C_{20}H_{26}O_5$ (M^+): 346.1779. Found: 346.1797. Anal. Calcd for $C_{20}H_{26}O_5$: C, 69.34; H, 7.56%. Found: C, 69.32; H, 7.64%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=13.3 min (minor), 14.2 min (major).

*4.4.2. 1-Butanoyl-7-endo-benzyloxy-5-methoxy-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (endo-**28c**).* Colorless viscous oil; $[\alpha]_D^{25}$ +114.6 (*c* 1.00, $CHCl_3$) (79% ee (*endo*)); IR (neat) 3012, 2962, 2881, 1724, 1601, 1458, 1362, 1304, 1269, 1215, 1169, 1095, 1041, 930 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.95 (3H, t, *J*=7.6 Hz), 1.69 (2H, m), 2.13 (1H, dd, *J*=13.4, 2.0 Hz), 2.57 (1H, ddd, *J*=6.3, 8.3, 18.5 Hz), 2.61 (1H, dd, *J*=13.4, 10.0 Hz), 2.74 (1H, ddd, *J*=6.6, 8.3, 18.5 Hz), 3.49 (3H, s), 4.45 (1H, d, *J*=12.0 Hz), 4.58 (1H, d, *J*=12.0 Hz), 4.65 (1H, dd, *J*=2.0, 10.0 Hz), 7.15–7.27 (5H, m), 7.47–7.51 (2H, m), 7.62–7.66 (1H, m), 8.04–8.06 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.7 (CH_3), 16.5 (CH_2), 41.3 (CH_2), 42.9 (CH_2), 52.0 (CH_3), 72.0 (CH_2), 77.1 (CH), 95.6 (C), 106.5 (C), 123.2 (CH), 126.7 (CH), 127.3 (CH), 127.7 (CH), 127.9 (CH), 128.7 (CH), 131.0 (C), 133.9 (CH), 137.4 (C), 144.1 (C), 189.5 (C), 203.7 (C); MS (EI) *m*/*z* 380 (M^+), 367, 330, 320, 310, 300, 289, 276, 262, 250, 230, 217, 201, 186, 176, 164, 152, 120, 109, 90, 78, 51, 24, 13. Anal. Calcd for $C_{23}H_{24}O_5$: C, 72.61; H, 6.36%. Found: C, 72.54; H, 6.41%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 0.5:99.5 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=43.0 min (minor), 72.6 min (major).

*4.4.3. 1-Butanoyl-7-endo-cyclohexyloxy-5-methoxy-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (endo-**28f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +171.4 (*c* 1.00, $CHCl_3$) (93% ee (*endo*)); IR (neat) 3021, 2936, 2859, 1728, 1701, 1603, 1522, 1456, 1362, 1300, 1269, 1215, 1169, 1098, 1063 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.95 (3H, t, *J*=7.3 Hz), 0.99–1.86 (10H, m), 1.62–1.74 (2H, m), 2.04 (1H, dd, *J*=12.9, 1.7 Hz), 2.59 (1H, dd, *J*=12.9, 9.5 Hz), 2.56 (1H, ddd, *J*=6.4, 8.1, 18.3 Hz), 2.74 (1H, ddd, *J*=6.6, 7.8, 18.3 Hz), 3.50 (3H, s), 3.44–3.54 (1H, m), 4.74 (1H, dd, *J*=1.7, 9.5 Hz), 7.43–7.51 (2H, m), 7.59–7.66 (1H, m), 7.96–8.03 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.8 (CH_3), 16.5 (CH_2), 23.7 (CH_2), 23.9 (CH_2), 25.8 (CH_2), 31.5 (CH_2), 32.3 (CH), 41.2 (CH_2), 43.6 (CH_2), 52.0 (CH_3), 74.8 (CH_2), 76.5 (CH), 95.5 (C), 106.9 (C), 123.2 (CH), 126.5 (CH), 128.6 (CH), 131.5 (C), 133.6 (CH), 144.1 (C), 189.7 (C), 203.8 (C); MS (EI) *m*/*z* 372 (M^+), 340, 313, 301, 290, 272, 258, 246, 230, 218, 201, 191, 187, 175, 163, 147, 129, 115, 103, 83, 71, 55, 39, 24, 13; HRMS (EI) calcd for $C_{22}H_{28}O_5$ (M^+): 372.1935. Found: 372.1953. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=13.8 min (minor), 17.8 min (major).

*4.4.4. 7-endo-Cyclohexyloxy-5-methoxy-1-propanoyl-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (endo-**29f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +176.9 (*c* 0.60, $CHCl_3$) (73% ee (*endo*)); ^{1}H NMR ($CDCl_3$) δ 0.99–1.78 (10H, m), 1.12 (3H, t, *J*=6.6 Hz), 2.03 (1H, dd, *J*=1.7, 13.2 Hz), 2.57 (1H, dq, *J*=7.1, 18.8 Hz), 2.58 (1H, dd, *J*=9.3, 13.2 Hz), 2.80 (1H, dq, *J*=7.1, 18.8 Hz), 3.49 (3H, s), 3.46–3.52 (1H, m), 4.74 (1H, dd, *J*=1.7, 9.3 Hz), 7.44–7.48 (2H, m), 7.60–7.64 (1H, m), 7.97–8.00 (1H, m); ^{13}C NMR ($CDCl_3$) δ 7.3 (CH_3), 23.8 (CH_2), 23.9 (CH_2), 25.9 (CH_2), 31.5 (CH_2), 32.3 (CH_2), 32.7 (CH_2), 43.7 (CH_2), 52.1 (CH), 74.9 (CH), 76.5 (CH), 95.6 (C), 106.9 (C), 123.2 (CH), 126.6 (CH), 128.7 (CH), 131.6 (C), 133.7 (CH), 144.1 (C), 189.8 (C), 204.6 (C). Satisfactory elemental analysis was not obtained. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=13.5 min (minor), 18.6 min (major).

*4.4.5. 7-endo-Benzyloxy-5-methoxy-1-(3-methylbutanoyl)-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**30c**).* Colorless viscous oil; $[\alpha]_D^{25}$ +133.7 (*c* 0.74, $CHCl_3$) (90% ee (*endo*)); IR (neat) 3035, 2978, 2943, 1724, 1601, 1458, 1304, 1269, 1173, 1099, 1041, 953, 887 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.14 (3H, t, *J*=6.8 Hz), 1.17 (3H, t, *J*=6.8 Hz), 2.12 (1H, dd, *J*=1.7, 13.2 Hz), 2.62 (1H, dd, *J*=9.8, 13.2 Hz), 3.08 (1H, quint, *J*=6.8 Hz), 3.50 (3H, s), 4.48 (1H, d, *J*=12.0 Hz), 4.63 (1H, d, *J*=12.0 Hz), 4.60 (1H, dd, *J*=1.7, 9.8 Hz), 7.16–7.25 (5H, m), 7.47–7.51 (2H, m), 7.62–7.66 (1H, m), 8.05–8.07 (1H, m); ^{13}C NMR ($CDCl_3$) δ 18.4 (CH_3), 18.7 (CH_3), 37.9 (CH), 42.9 (CH_2), 52.0 (CH_3), 72.0 (CH_2), 77.8 (CH), 96.2 (C), 106.4 (C), 123.2 (CH), 126.9 (CH), 127.3 (CH), 127.8 (CH), 128.0 (CH), 128.8 (CH), 130.9 (C), 134.0 (CH), 137.5 (C), 144.1 (C), 189.1 (C), 207.7 (C); MS (EI) *m*/*z* 380 (M^+), 362, 348, 310, 289, 247, 231, 215, 201, 187, 174, 161, 147, 129, 115, 104, 91, 71, 54, 43, 27, 15, 3. Anal. Calcd for $C_{23}H_{24}O_5$: C, 72.61; H, 6.36%. Found: C, 72.55; H, 6.37%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=23.2 min (major), 26.8 min (minor).

*4.4.6. 7-endo-Cyclohexyloxy-5-methoxy-1-(3-methylbutanoyl)-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**30f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +177.3 (*c* 1.00, $CHCl_3$) (88% ee (*endo*)); IR (neat) 3568, 3021, 2936, 2858, 2401, 1728, 1703, 1602, 1415, 1366, 1362, 1269, 1215, 1169, 1169, 1098, 1064, 758, 530 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.84–1.70 (10H, m), 0.94 (3H, d, *J*=6.5 Hz), 0.97 (3H, d, *J*=6.8 Hz), 2.06 (1H, dd, *J*=13.2, 1.7 Hz), 2.25 (1H, m), 2.47 (1H, dd, *J*=6.5, 17.8 Hz) 2.58 (1H, dd, *J*=13.2, 9.2 Hz), 2.63 (1H, dd, *J*=6.8, 17.8 Hz), 3.42–3.54 (1H, m), 3.49 (3H, s), 4.72 (1H, dd, *J*=1.7, 9.2 Hz), 7.41–7.52 (2H, m), 7.58–7.67 (1H, m), 7.94–8.03 (1H, m); ^{13}C NMR ($CDCl_3$) δ 22.6 (CH_3), 22.7 (CH_3), 23.7 (CH), 23.7 (CH_2), 23.8 (CH_2), 25.8 (CH_2), 31.5 (CH_2), 32.2 (CH_2), 43.5 (CH_2), 48.1 (CH_2), 52.0 (CH_3), 74.8 (CH), 76.4 (CH), 95.4 (C), 106.8 (C),123.1 (CH), 126.5 (CH), 128.6 (CH), 131.5 (C), 133.6 (CH), 144.1 (C), 189.6 (C), 203.3 (C); MS (EI) *m*/*z* 386 (M^+), 354, 327, 304, 286, 272, 261, 244, 232, 219, 201, 200, 187, 173, 161, 147, 129, 115, 103, 85, 69, 57, 39, 26, 13; HRMS (EI) calcd for $C_{23}H_{30}O_5$ (M^+): 386.2092. Found: 386.2106. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 0.5:99.5 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=14.9 min (minor), 18.0 min (major).

*4.4.7. 7-endo-Cyclohexyloxy-5-methoxy-1-pentanoyl-8-oxabenzo-[c]bicyclo[3.2.1]octan-2-one (endo-**31f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +180.5 (*c* 1.00, $CHCl_3$) (93% ee (*endo*)); IR (neat) 3020, 2935, 1728, 1701, 1423, 1302, 1269, 1215, 1168, 1097, 1047, 929, 771, 669 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, *J*=7.3 Hz), 0.95–1.74 (10H, m), 1.34 (2H, m),1.64 (2H, m) 2.03 (1H, dd, *J*=1.7, 12.9 Hz), 2.56 (1H, m), 2.58 (1H, dd, *J*=9.5, 12.9 Hz), 2.75 (1H, ddd, *J*=6.3, 8.3, 18.0 Hz), 3.40–3.54 (1H, m), 3.50 (3H, s), 4.73 (1H, dd, *J*=1.7, 9.5 Hz), 7.42–7.50 (2H, m), 7.59–7.66 (1H, m), 7.95–8.02 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.9 (CH_3), 22.2 (CH_2), 23.6 (CH_2), 23.8 (CH_2), 25.1 (CH_2), 25.8 (CH_2), 31.4 (CH_2), 32.2 (CH_2), 38.9 (CH_2), 43.5 (CH_2), 51.9 (CH_3), 74.8 (CH), 76.4 (CH), 95.5 (C), 106.8 (C), 123.1 (CH), 126.4 (CH), 128.5 (CH), 131.4 (C), 133.6 (CH), 144.1 (C), 189.7 (C), 203.9 (C); MS (EI) *m/z* 386 (M^+), 354, 327, 304, 286, 272, 260, 244, 231, 218, 201, 200, 187, 173, 161, 147, 129, 115, 103, 83, 71, 57, 37, 26, 13; HRMS (EI) calcd for $C_{23}H_{30}O_5$ (M^+): 386.2092. Found: 386.2112. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=13.3 min (minor), 17.8 min (major).

*4.4.8. 7-endo-Cyclohexyloxy-5-methoxy-1-(3-methylbutanoyl)-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**32f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +177.3 (*c* 1.00, $CHCl_3$) (88% ee (*endo*)); IR (neat) 3568, 3021, 2936, 2858, 2401, 1728, 1703, 1602, 1415, 1366, 1362, 1269, 1215, 1169, 1169, 1098, 1064, 758, 530 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.84–1.70 (10H, m), 0.94 (3H, d, *J*=6.5 Hz), 0.97 (3H, d, *J*=6.8 Hz), 2.06 (1H, dd, *J*=13.2, 1.7 Hz), 2.25 (1H, m), 2.47 (1H, dd, *J*=6.5, 17.8 Hz) 2.58 (1H, dd, *J*=13.2, 9.2 Hz), 2.63 (1H, dd, *J*=6.8, 17.8 Hz), 3.42–3.54 (1H, m), 3.49 (3H, s), 4.72 (1H, dd, *J*=1.7, 9.2 Hz), 7.41–7.52 (2H, m), 7.58–7.67 (1H, m), 7.94–8.03 (1H, m); ^{13}C NMR ($CDCl_3$) δ 22.6 (CH_3), 22.7 (CH_3), 23.7 (CH), 23.7 (CH_2), 23.8 (CH_2), 25.8 (CH_2), 31.5 (CH_2), 32.2 (CH_2), 43.5 (CH_2), 48.1 (CH_2), 52.0 (CH_3), 74.8 (CH), 76.4 (CH), 95.4 (C), 106.8 (C),123.1 (CH), 126.5 (CH), 128.6 (CH), 131.5 (C), 133.6 (CH), 144.1 (C), 189.6 (C), 203.3 (C); MS (EI) *m/z* 386 (M^+), 354, 327, 304, 286, 272, 261, 244, 232, 219, 201, 200, 187, 173, 161, 147, 129, 115, 103, 85, 69, 57, 39, 26, 13; HRMS (EI) calcd for $C_{23}H_{30}O_5$ (M^+): 386.2092. Found: 386.2106. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 0.5:99.5 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=14.9 min (minor), 18.0 min (major).

*4.4.9. 7-endo-Cyclohexyloxy-1-hexanoyl-5-methoxy-8-oxabenzo[c]-bicyclo[3.2.1]-octan-2-one (endo-**33f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +154.1 (*c* 0.80, $CHCl_3$) (84% ee, (*endo*)); IR (neat) 3021, 2934, 2859, 1730, 1701, 1651, 1603, 1507, 1456, 1362, 1300, 1269, 1215, 1167, 1098, 1065 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.89 (3H, t, *J*=7.3 Hz), 1.01–1.77 (10H, m), 1.04, (2H, m), 1.31 (2H, m), 1.65 (2H, m), 2.03 (1H, dd, *J*=1.7, 12.9 Hz), 2.56 (1H, ddd, *J*=6.3, 8.1, 18.3 Hz), 2.58 (1H, dd, *J*=9.3, 12.9 Hz), 2.75 (1H, ddd, *J*=6.6, 8.3, 18.3 Hz), 3.49 (3H, s), 3.45–3.52 (1H, m), 4.73 (1H, dd, *J*=1.7, 9.3 Hz), 7.44–7.48 (2H, m), 7.60–7.64 (1H, m), 7.96–8.00 (1H, m); ^{13}C NMR ($CDCl_3$) δ 14.1 (CH_3), 22.6 (CH_2), 22.8 (CH_2), 23.8 (CH_2), 23.9 (CH_2), 25.9 (CH_2), 31.4 (CH_2), 31.5 (CH_2), 32.3 (CH_2), 39.4 (CH_2), 43.6 (CH_2), 52.1 (CH_3), 74.9 (CH), 76.5 (CH), 95.6 (C), 106.9 (C), 123.2 (CH), 126.6 (CH), 128.6 (CH), 131.6 (C), 133.7 (CH), 144.1 (C), 189.8 (C), 204.1 (C); MS (EI) *m/z* 400 (M^+), 368, 341, 318, 301, 275, 258, 246, 231, 215, 201, 187, 173, 159, 145, 129, 116, 103, 83, 69, 55, 37, 24; HRMS (EI) calcd for $C_{24}H_{32}O_5$ (M^+): 400.2248. Found: 400.2242. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=42.0 min (minor), 55.7 min (major).

*4.4.10. 1-(Cylohexylcarbonyl)-7-endo-cyclohexyloxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**34f**).* Colorless prisms (hexane); mp 95–96 °C; $[\alpha]_D^{25}$ +163.7 (*c* 1.00, $CHCl_3$) (96% ee (*endo*)); IR (KBr) 3021, 2936, 2857, 1728, 1699, 1557, 1539, 1520, 1454, 1300, 1267, 1217, 1167, 1098, 1051, 974 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.98–1.92 (20H, m), 2.01 (1H, dd, *J*=1.7, 12.9 Hz), 2.58 (1H, dd, *J*=9.3, 12.9 Hz), 2.82 (1H, tt, *J*=3.2, 11.2 Hz), 3.50 (3H, s), 3.52–3.56 (1H, m), 4.66 (1H, dd, *J*=1.7, 9.3 Hz), 7.44–7.48 (2H, m), 7.60–7.64 (1H, m), 7.98–8.00 (1H, m); ^{13}C NMR ($CDCl_3$) δ 23.8 (CH_2), 23.9 (CH_2), 25.7 (CH_2), 25.9 (CH_2), 26.0 (CH_2), 28.5 (CH_2), 28.9 (CH_2), 31.5 (CH_2), 32.4 (CH_2), 43.5 (CH_2), 47.7 (CH), 52.0 (CH_3), 75.5 (CH), 76.4 (CH), 96.0 (C), 106.7 (C), 123.2 (CH), 126.7 (CH), 128.6 (CH), 131.5 (C), 133.6 (CH), 144.0 (C), 189.3 (C), 207.1 (C); MS (EI) *m/z* 412 (M^+), 380, 353, 330, 287, 270, 201, 187, 174, 161, 147, 129, 103, 83, 55, 37, 24; HRMS (EI) calcd for $C_{25}H_{32}O_5$ (M^+): 412.2248. Found: 412.2234. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=16.0 min (major), 19.5 min (minor).

*4.4.11. 7-endo-Cyclohexyloxy-5-methoxy-1-(phenylacetyl)-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**35f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +165.7 (*c* 1.00, $CHCl_3$) (92% ee (*endo*)); IR (neat) 3020, 2938, 1734, 1701, 1302, 1269, 1215, 1165, 1098, 1067, 1028, 976, 669 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.84–1.72 (10H, m), 2.05 (1H, dd, *J*=13.1, 1.7 Hz), 2.60 (1H, dd, *J*=13.1, 9.5 Hz), 3.41–3.56 (1H, m), 3.88 (1H, d, *J*=17.1 Hz), 4.06 (1H, d, *J*=17.1 Hz), 4.75 (1H, dd, *J*=1.7, 9.5 Hz), 7.44–7.53 (2H, m), 7.61–7.67 (1H, m), 7.96–8.04 (1H, m); ^{13}C NMR ($CDCl_3$) δ 23.6 (CH_2), 23.8 (CH_2), 25.8 (CH_2), 31.3 (CH_2), 32.2 (CH_2), 43.6 (CH_2), 45.9 (CH_2), 52.1 (CH_3), 74.8 (CH), 76.4 (CH), 95.7 (C), 107.0 (C), 123.2 (CH), 126.5 (CH), 126.7 (CH), 128.2 (CH), 128.6 (CH), 129.8 (CH), 131.4 (C), 133.2 (C), 133.7 (CH), 144.0 (C), 189.5 (C), 201.1 (C); MS (EI) *m/z* 420 (M^+), 388, 360, 338, 307, 294, 278, 262, 247, 234, 219, 203, 187, 173, 160, 147, 129, 104, 91, 77, 55, 37, 24; HRMS (EI) calcd for $C_{26}H_{28}O_5$ (M^+): 420.1935. Found: 420.1942. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=24.2 min (minor), 39.0 min (major).

*4.4.12. 7-endo-Cyclohexyloxy-5-methoxy-1-(3-phenylpropanoyl)-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**36f**).* Colorless viscous oil; $[\alpha]_D^{25}$ +135.1 (*c* 1.00, $CHCl_3$) (77% ee (*endo*)); IR (neat) 2935, 2859, 1730, 1705, 1602, 1497, 1454, 1362, 1302, 1269, 1215, 1165, 1096, 1046, 754, 700, 505 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.83–1.84 (10H, m), 2.03 (1H, dd, *J*=13.1, 1.7 Hz), 2.56 (1H, dd, *J*=13.1, 9.5 Hz), 2.89 (1H, m), 2.99 (2H, m), 3.07 (1H, m), 3.50 (3H, s), 3.40–3.54 (1H, m), 4.71 (1H, dd, *J*=1.7, 9.5 Hz), 7.39–7.53 (2H, m), 7.57–7.66 (1H, m), 7.93–8.01 (1H, m); ^{13}C NMR ($CDCl_3$) δ 23.7 (CH_2), 23.8 (CH_2), 25.8 (CH_2), 29.2 (CH_2), 31.5 (CH_2), 32.3 (CH_2), 41.0 (CH_2), 43.7 (CH_2), 52.1 (CH_3), 74.9 (CH), 76.6 (CH), 95.4 (C), 107.0 (C), 123.2 (CH), 125.8 (CH), 126.5 (CH), 128.1 (CH), 128.2 (CH), 128.6 (CH), 131.5 (C), 133.7 (CH), 140.8 (C), 144.0, (C)189.7 (C), 202.8 (C); MS (EI) *m/z* 434 (M^+), 402, 375, 352, 334, 309, 292, 279, 263, 248, 231, 217, 201, 187, 173, 149, 129, 105, 91, 71, 57, 39, 26, 13; HRMS (EI) calcd for $C_{27}H_{30}O_5$ (M^+): 434.2092. Found: 434.2104. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 2:98 *i*-PrOH/hexane, flow 0.2 mL/min, 35 °C) t_R=44.4 min (minor), 47.1 min (major).

*4.4.13. 1-Butanoyl-7-endo-(tert-butyldimethylsilyl)oxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (endo-**38**).* Colorless viscous oil; $[\alpha]_D^{25}$ −40.0 (*c* 1.00, $CHCl_3$) (19% ee (*endo*)); IR (neat) 2951, 2893, 1948, 1724, 1604, 1462, 1373, 1304, 1261, 1215, 1169, 1111, 1034, 949, 837 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ −0.08 (3H, s), 0.06 (3H, s), 0.58 (9H, s), 0.94 (3H, t, *J*=7.3 Hz), 1.68 (2H, m), 1.92 (1H, dd, *J*=12.9, 1.5 Hz), 2.55 (1H, ddd, *J*=6.3, 8.3, 18.3 Hz), 2.55 (1H, dd, *J*=12.9, 8.8 Hz), 2.74 (1H, ddd, *J*=6.6, 8.3, 18.3 Hz), 3.49 (3H, s), 4.92 (1H, dd, *J*=1.5, 8.8 Hz), 7.43–7.47 (2H, m), 7.59–7.63 (1H, m), 7.96–7.98 (1H, m); ^{13}C NMR ($CDCl_3$) δ −5.2 (CH_3), −5.0 (CH_3), 13.8 (CH_3), 16.5 (CH_2), 17.6 (C), 25.3 (CH_3), 41.2 (CH_2), 45.4 (CH_2), 52.1 (CH_3), 71.3 (CH), 95.1 (C), 107.1 (C), 123.1 (CH), 126.5 (CH), 128.5 (CH), 131.7 (C), 133.6 (CH), 144.0 (C), 189.4 (C), 203.4 (C); MS (EI) *m/z* 404 (M^+), 388, 374, 362, 346, 328, 315, 302, 287, 273, 261, 250, 231, 217, 204, 188, 175, 159, 146, 138, 115, 101, 85, 74, 59, 47, 35, 24, 12. Anal. Calcd for $C_{22}H_{32}O_5Si$: C, 65.31; H, 7.97%. Found: C, 65.17; H, 8.09%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak OD-H, 1:800 *i*-PrOH/hexane, flow 0.2 mL/min, 35 °C) t_R=6.7 min (minor), 9.0 min (major).

*4.4.14. 1-Butanoyl-7-endo-butanoyloxy-5-methoxy-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (endo-**39**).* Colorless viscous oil; IR (neat)

3028, 2966, 1736, 1601, 1458, 1369, 1304, 1269, 1161, 1095, 1034, 933 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.72 (3H, t, J=7.3 Hz), 0.95 (3H, t, J=7.3 Hz), 1.39 (2H, m), 1.68 (2H, m), 1.96 (1H, dd, J=13.9, 2.2 Hz), 2.07 (2H, m), 2.55 (1H, ddd, J=6.6, 8.3, 18.3 Hz), 2.72 (1H, ddd, J=6.6, 8.1, 18.3 Hz), 2.84 (1H, dd, J=13.9, 9.5 Hz), 3.52 (3H, s), 5.75 (1H, dd, J=2.2, 9.5 Hz), 7.49–7.54 (2H, m), 7.65–7.69 (1H, m), 8.05–8.07 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.4 (CH_3), 13.7 (CH_3), 16.5 (CH_2), 18.1 (CH_2), 35.9 (CH_2), 41.1 (CH_2), 42.6 (CH_2), 52.2 (CH_3), 71.1 (CH), 92.6 (C), 106.8 (C), 123.2 (CH), 127.0 (CH), 128.9 (CH), 130.5 (C), 134.3 (CH), 144.3 (C), 171.6 (C), 188.5 (C), 202.1 (C); MS (EI) m/z 360 (M^+), 301, 290, 272, 258, 244, 229, 213, 202, 187, 173, 161, 147, 129, 115, 103, 91, 77, 57, 37, 24, 13. Anal. Calcd for $C_{20}H_{24}O_6$: C, 66.65; H, 6.71%. Found: C, 66.35; H, 6.44%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:9 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=10.5 min (major), 21.3 min (minor).

*4.4.15. 1-Butanoyl-7-endo-butyl-5-methoxy-8-oxabenzo[c]bicyclo-[3.2.1]octan-2-one (endo-**40**).* Colorless viscous oil; IR (neat) 2951, 2873, 1724, 1597, 1454, 1400, 1373, 1296, 1215, 1165, 1088, 1038, 976, 899 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.80 (3H, t, J=7.1 Hz), 0.93 (3H, t, J=7.3 Hz), 1.11–1.23 (4H, m), 1.61–1.67 (4H, m), 1.67 (1H, dd, J=12.6, 4.9 Hz), 2.51 (1H, ddd, J=6.3, 7.8, 18.1 Hz), 2.57 (1H, dd, J=12.6, 11.7 Hz), 2.72 (1H, ddd, J=6.8, 7.8, 18.1 Hz), 2.80 (1H, dddd, J=3.9, 8.5, 4.9, 11.7 Hz), 3.52 (3H, s), 7.46–7.50 (2H, m), 7.64–7.68 (1H, m), 8.02–8.04 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.8 (CH_3), 14.0 (CH_3), 16.6 (CH_2), 22.5 (CH_2), 31.1 (CH_2), 32.0 (CH_2), 39.7 (CH_2), 40.1 (CH), 41.3 (CH_2), 51.9 (CH_3), 94.6 (C), 106.6 (C), 122.8 (CH), 127.0 (CH), 128.6 (CH), 130.1 (C), 134.3 (CH), 146.2 (C), 191.3 (C), 203.9 (C); MS (EI) m/z 330 (M^+), 314, 302, 288, 276, 259, 250, 241, 232, 217, 199, 186, 174, 167, 157, 119, 108, 101, 91, 78, 51, 24, 12, 3. Anal. Calcd for $C_{20}H_{26}O_4$: C, 72.70; H, 7.93%. Found: C, 72.50; H, 8.11%. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:400 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=17.5 min (minor), 18.9 min (major).

*4.4.16. 1-Butanoyl-7-endo-butoxymethyl-5-methoxy-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (endo-**41**).* Colorless viscous oil; ^{1}H NMR ($CDCl_3$) δ 0.74 (3H, t, J=7.3 Hz), 0.93 (3H, t, J=7.3 Hz), 1.02 (2H, sext, J=7.3 Hz), 1.17 (2H, m), 1.61–1.71 (2H, m), 2.10 (1H, dd, J=5.6, 13.2 Hz), 2.52 (1H, ddd, J=6.6, 8.1, 18.1 Hz), 2.51 (1H, dd, J=11.5, 13.2 Hz), 2.71 (1H, ddd, J=6.6, 7.8, 18.1 Hz), 3.02–3.09 (1H, m), 3.12 (2H, dt, J=6.3, 1.5 Hz), 3.16 (1H, dd, J=6.1, 9.5 Hz), 3.50 (1H, dd, J=3.7, 9.5 Hz), 3.52 (3H, s), 7.43–7.48 (2H, m), 7.60–7.64 (1H, m), 7.97–7.99 (1H, m). The other spectroscopic data and satisfactory elemental analysis were not obtained because of a small amount of the product.

*4.4.17. 1-Butanoyl-5-methoxy-7-phenyl-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (**42**).* Mixture of diastereomer, 91:9; Colorless viscous oil; IR (neat) 3062, 2958, 2904, 1728, 1693, 1597, 1496, 1454, 1373, 1296, 1200, 1161, 1041, 987, 914, 856 cm^{-1}; ^{1}H NMR ($CDCl_3$) Major: δ 0.93 (3H×0.91, t, J=7.6 Hz), 1.68 (2H×0.91, m), 2.41 (1H×0.91, dd, J=13.2, 4.6 Hz), 2.52 (1H×0.91, dt, J=7.1, 18.3 Hz), 2.74 (1H×0.91, dt, J=7.1, 18.3 Hz), 2.89 (1H×0.91, dd, J=13.2, 12.2 Hz), 3.58 (3H×0.91, s), 4.39 (1H×0.91, dd, J=4.6, 12.2 Hz), 6.80–6.82 (2H×0.91, m), 7.02–7.11 (3H×0.91, m), 7.46–7.51 (1H×0.91, m), 7.60–7.62 (1H×0.91, m), 7.70–7.84 (2H×0.91, m); Minor: δ 0.98 (3H×0.09, t, J=7.3 Hz), 1.72 (2H×0.09, m), 2.20 (1H×0.09, dd, J=14.6, 8.3 Hz), 2.61 (1H×0.09, ddd, J=6.3, 8.1, 18.1 Hz), 2.82 (1H×0.09, ddd, J=6.3, 8.3, 18.1 Hz), 3.16 (1H×0.09, dd, J=14.6, 11.0 Hz), 3.54 (3H×0.09, s), 3.78 (1H×0.09, dd, J=8.3, 11.0 Hz), 6.66–6.71 (3H×0.09, m), 7.02–7.14 (2H×0.09, m), 7.29–7.34 (2H×0.09, m), 7.40–7.44 (1H×0.09, m), 8.07–8.10 (1H×0.09, m); ^{13}C NMR ($CDCl_3$) Major: δ 13.8 (CH_3), 16.7 (CH_2), 41.3 (CH_2), 41.5 (CH_2), 44.7 (CH), 52.4 (CH_3), 95.5 (C), 107.0 (C), 123.2 (CH), 126.9 (CH), 127.9 (CH), 128.4 (CH), 128.9 (CH), 131.4 (C), 134.5 (CH), 136.3 (C), 144.7 (C) 190.7 (C), 203.4 (C); Minor: 13.8 (CH_3), 16.6 (CH_2), 33.1 (CH_2), 41.1 (CH_2), 50.9 (CH_3), 52.7 (CH), 90.3 (C), 109.7 (C), 126.0 (CH), 127.0 (CH), 127.1 (CH), 127.7 (CH), 130.1 (C), 133.2 (CH), 135.8 (C), 140.8 (C), 191.4 (C), 203.8 (C); MS (EI) m/z 350 (M^+), 291, 274, 250, 231, 219, 191, 175, 161, 149, 129, 115, 104, 91, 77, 57, 39, 25, 12. Anal. Calcd for $C_{22}H_{22}O_4$: C, 75.41; H, 6.33%. Found: C, 75.42; H, 6.32%. The enantiomeric excess of major adduct was determined by HPLC analysis (DAICEL Chiralpak AD-H, 0.5:99.5 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=30.5 min (minor), 38.2 min (major).

*4.4.18. 6-endo-7-endo-1-Butanoyl-5-methoxy-8-oxabenzo[c]-tetrahydrofuro[3,2-f]bicyclo[3.2.1]-octan-2-one (endo-**43**).* Colorless solid; mp 59–60.5 °C; $[\alpha]_D^{25}$ −137.9 (c 1.00, $CHCl_3$) (54% ee (*endo*)); IR (neat) 3073, 3034, 2957, 2874, 2845, 2361, 2342, 1728, 1699, 1599, 1454, 1404, 1379, 1368, 1333, 1304, 1287, 1256, 1221, 1198, 1167, 1119, 1096, 1080, 1051, 1048, 1015 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.96 (3H, t, J=7.3 Hz), 1.52 (1H, m), 1.65–1.76 (2H, m), 1.97 (1H, m), 2.57 (1H, ddd, J=6.6, 8.1, 18.1 Hz), 2.70 (1H, dt, J=8.1, 8.1 Hz), 2.77 (1H, ddd, J=6.6, 8.1, 18.1 Hz), 3.30 (1H, dt, J=2.2, 9.0 Hz), 3.51 (3H, s), 3.66 (1H, dt, J=4.4, 9.0 Hz), 5.12 (1H, d, J=8.3 Hz), 7.44–7.56 (2H, m), 7.63–7.71 (1H, m), 8.04–8.10 (1H, m); ^{13}C NMR ($CDCl_3$) δ 13.7 (CH_3), 16.6 (CH_2), 26.5 (CH_2), 41.1 (CH_2), 52.4 (CH_3), 52.5 (CH), 71.8 (CH_2), 84.9 (CH), 94.4 (C), 108.7 (C), 125.2 (CH), 127.0 (CH), 129.2 (CH), 132.0 (C), 133.3 (CH), 140.8 (C), 188.7 (C), 202.4 (C); MS (EI) m/z 316 (M^+), 256, 246, 231, 217, 203, 187, 176, 163, 147, 129, 115, 104, 91, 77, 68, 55, 39, 24, 12. Anal. Calcd for $C_{18}H_{20}O_5$: C, 68.34; H, 6.37%. Found: C, 68.48; H, 6.49%. The enantiomeric excess of major adduct was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:19 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=28.0 min (major), 31.4 min (minor).

*4.4.19. 1-Butanoyl-5,7-endo-dimethoxy-7-exo-methyl-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (endo-**44**).* Colorless viscous oil; $[\alpha]_D^{25}$ +43.7 (c 0.50, $CHCl_3$) (8% ee (*endo*)); IR (neat) 3021, 2967, 2833, 2401, 1734, 1967, 1601, 1520, 1456, 1301, 1277, 1254, 1219, 1147, 1086, 1003 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.93 (3H, t, J=7.3 Hz), 1.35 (3H, s), 1.64 (2H, sext, J=7.3 Hz), 1.92 (1H, d, J=13.6 Hz), 2.54 (1H, dt, J=7.3, 18.0 Hz), 2.78 (1H, dt, J=7.3, 18.0 Hz), 2.77 (1H, d, J=13.6 Hz), 3.22 (3H, s), 3.60 (3H, s), 7.41–8.03 (4H, m); ^{13}C NMR ($CDCl_3$) δ 13.8 (CH_3), 16.4 (CH_2), 20.8 (CH_3), 42.6 (CH_2), 46.0 (CH_2), 50.6 (CH_3), 52.0 (CH_3), 85.2 (C), 98.2 (C), 105.8 (C), 122.0 (CH), 127.7 (CH), 128.7 (CH), 129.3 (C), 134.3 (CH), 146.6 (C), 188.1 (C), 200.6 (C). Satisfactory elemental analysis was not obtained. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=45.7 min (minor), 53.6 min (major).

*4.4.20. 1-Butanoyl-5,7-exo-dimethoxy-7-endo-methyl-8-oxabenzo-[c]bicyclo[3.2.1]octan-2-one (exo-**44**).* Colorless viscous oil; $[\alpha]_D^{25}$ +101.4 (c 0.80, $CHCl_3$) (34% ee (*exo*)); IR (neat) 3021, 2967, 2936, 2833, 2401, 1734, 1697, 1601, 1520, 1454, 1301, 1298, 1277, 1147, 1086, 1003, 970 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.93 (3H, t, J=7.6 Hz), 1.42 (3H, s), 1.64 (2H, m), 2.37 (2H, s), 2.51 (1H, dt, J=7.6, 18.0 Hz), 2.70 (1H, dt, J=7.6, 18.0 Hz), 3.18 (3H, s), 3.54 (3H, s), 7.41–8.07 (4H, m); ^{13}C NMR ($CDCl_3$) δ 13.7 (CH_3), 16.4 (CH_2), 22.0 (CH_3), 42.2 (CH_2), 50.5 (CH_2), 51.8 (CH_3), 52.0 (CH_3), 84.0 (C), 97.7 (C), 104.7 (C), 122.3 (CH), 127.2 (CH), 128.5 (CH), 130.4 (C), 133.7 (CH), 144.4 (C), 187.2 (C), 202.4 (C). Satisfactory elemental analysis was not obtained. The enantiomeric excess was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=20.8 min (major), 27.1 min (minor).

*4.4.21. 1-Butanoyl-7-butoxy-7-(tert-butyldimethylsilyl)oxy-5-methoxy-8-oxabenzo[c]bicyclo[3.2.1]-octan-2-one (**45**).* Mixture of diastereomer, 74:26; Yellow viscous oil; IR (neat) 3047, 2958, 2873, 1944, 1732, 1651, 1604, 1462, 1284, 1180, 1072, 1018 cm^{-1}; ^{1}H NMR ($CDCl_3$) Major: δ −0.28 (3H, s), 0.11 (3H, s), 0.63 (9H, s), 0.91 (3H, t,

J=7.3 Hz), 1.00 (3H, t, J=7.3 Hz), 1.30–1.39 (2H, m), 1.47–1.54 (2H, m), 1.63–1.70 (1H, m), 1.77–1.87 (1H, m), 2.10 (1H, d, J=13.4 Hz), 2.82 (1H, ddd, J=5.6, 9.8, 17.8 Hz), 2.95 (1H, d, J=13.4 Hz), 3.08 (1H, ddd, J=5.6, 9.5, 17.8 Hz), 3.40 (1H, dt, J=6.3, 9.0 Hz), 3.56 (3H, s), 3.52–3.59 (1H, m), 7.40–7.47 (2H, m), 7.58–7.60 (1H, m), 7.97–7.99 (1H, m); Minor: δ 0.14 (3H, s), 0.20 (3H, s), 0.75 (3H, t, J=7.3 Hz), 0.89 (9H, s), 0.94 (3H, t, J=7.3 Hz), 1.04–1.10 (2H, m), 1.18–1.25 (2H, m), 1.60–1.69 (2H, m), 2.44 (1H, d, J=12.7 Hz), 2.62 (1H, ddd, J=6.6, 8.5, 18.5 Hz), 2.72 (1H, ddd, J=6.6, 8.3, 18.5 Hz), 2.74 (1H, d, J=12.7 Hz), 3.43 (1H, dt, J=6.3, 9.5 Hz), 3.55 (3H, s), 3.79 (1H, dt, J=6.3, 9.5 Hz), 7.38–7.46 (2H, m), 7.57–7.61 (1H, m), 7.97–7.99 (1H, m); ^{13}C NMR ($CDCl_3$) Major: δ −4.4 (CH_3), −2.6 (CH_3), 14.0 (CH_3), 14.1 (CH_3), 17.0 (CH_2), 17.8 (C), 19.3 (CH_2), 25.2 (CH_3), 32.0 (CH_2), 43.5 (CH_2), 46.4 (CH_2), 52.2 (CH_3), 64.4 (CH_2), 98.2 (C), 105.2 (C), 107.0 (C), 122.3 (CH), 127.4 (CH), 128.7 (CH), 130.7 (C), 133.8 (CH), 144.3 (C), 187.6 (C), 201.2 (C); MS (EI) m/z 476 (M^+), 461, 405, 387, 330, 317, 287, 261, 247, 230, 217, 202, 186, 173, 160, 147, 129, 105, 89, 73, 57, 43, 29. Anal. Calcd for $C_{26}H_{40}O_6Si$: C, 65.51; H, 8.46%. Found: C, 65.41; H, 8.47%. The enantiomeric excess of major adduct was determined by HPLC analysis (DAICEL Chiralpak OD-3, 1:200 EtOH/hexane, flow 0.5 mL/min, 35 °C) t_R=10.2 min (major), 13.5 min (minor).

*4.4.22. 1-Butanoyl-7-butoxy-5-methoxy-7-phenyl-8-oxabenzo[c]-bicyclo[3.2.1]octan-2-one (**46**).* Mixture of diastereomer, 74:26; Colorless viscous oil; $[\alpha]_D^{25}$ +77.8 (c 1.00, $CHCl_3$) (74:26 Mixture of diastereomer, 44% ee (major), 44% ee (minor)); IR (neat) 3066, 2958, 2877, 1736, 1601, 1454, 1369, 1273, 1153, 1072, 1018, 818 cm^{-1}; ^{1}H NMR ($CDCl_3$) Major: δ 0.64 (3H, t, J=7.3 Hz), 0.67 (3H, t, J=7.3 Hz), 0.79–1.40 (6H, m), 2.16 (1H, ddd, J=5.6, 9.0, 17.8 Hz), 2.41 (1H, ddd, J=6.3, 9.0, 17.8 Hz), 2.83 (1H, d, J=14.4 Hz), 2.90 (1H, d, J=14.4 Hz), 2.95 (1H, ddd, J=6.1, 7.6, 9.5 Hz), 3.48 (1H, ddd, J=5.6, 6.3, 9.5 Hz), 3.66 (3H, s), 7.22–7.67 (8H, m), 8.05–8.07 (1H, m); Minor: δ 0.88 (3H, t, J=7.3 Hz), 0.96 (3H, t, J=7.3 Hz), 0.79–1.40 (2H, m), 1.48–1.54 (2H, m), 1.61–1.72 (2H, m), 2.59 (1H, ddd, J=6.6, 7.3, 18.1 Hz), 2.82–2.98 (1H, m), 2.84 (1H, m), 2.93 (1H, d, J=13.7 Hz), 3.10 (2H, m), 3.64 (3H, s), 6.92–7.17 (5H, m), 7.22–7.67 (4H, m); ^{13}C NMR ($CDCl_3$) Major: δ 13.6 (CH_3), 13.7 (CH_3), 16.3 (CH_2), 19.0 (CH_2), 31.8 (CH_2), 42.7 (CH_2), 48.3 (CH_2), 52.7 (CH_3), 66.0 (CH_2), 88.2 (C), 99.0 (C), 105.8 (C), 122.3 (CH), 126.3 (CH), 127.5 (CH), 128.1 (CH), 128.6 (CH), 131.0 (C), 133.4 (CH), 141.1 (C), 144.3 (C), 186.6 (C); Minor: 13.9 (CH_3), 14.0 (CH_3), 16.4 (CH_2), 19.5 (CH_2), 31.9 (CH_2), 42.5 (CH_2), 45.4 (CH_2), 52.0 (CH_3), 63.7 (CH_2), 89.8 (C), 97.0 (C), 106.6 (C), 122.6 (CH), 126.3 (CH), 127.6 (CH), 128.1 (CH), 128.9 (CH), 131.1 (C), 134.0 (CH), 136.0 (C), 143.9 (C), 185.6 (C); MS (EI) m/z 422 (M^+), 390, 363, 348, 333, 317, 289, 263, 246, 231, 218, 203, 189, 175, 161, 147, 129, 117, 105, 91, 71, 57, 41, 27, 15. Anal. Calcd for $C_{26}H_{30}O_5$: C, 73.91; H, 7.16%. Found: C, 73.79; H, 7.16%. The enantiomeric excess of major adduct was determined by HPLC analysis (DAICEL Chiralpak AD-H, 2:98 i-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=33.3 min (minor), 38.6 min (major). The enantiomeric excess of minor adduct was determined by HPLC analysis (DAICEL Chiralpak AD-H, 2:98 i-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=27.5 min (minor), 52.2 min (major).

4.5. General procedure for the reaction of diazo diketones 47–52 with olefins was exemplified the reaction of 1-diazo-2,5-hexandione (47) with butyl vinyl ether (2a) catalyzed by (4*S*,5*S*)-Pybox-Ph$_2$–Lu(III) Complex

A solution of 2,6-bis[(4*S*,5*S*)-4,5-diphenyl-2-oxazolin-2-yl]pyridine ((4*S*,5*S*)-Pybox-Ph$_2$, 26.1 mg, 0.05 mmol) in THF (1.5 mL) was added to a solution of Lu(OTf)$_3$ (30.0 mg, 0.05 mmol) in THF (1 mL). After stirring the mixture for 2 h, the solvent was removed under reduced pressure and resulting solid was dried in vacuo at room temperature for 5 h. A solution of Lu(III)–Pybox complex in CH_2Cl_2 (3 mL, purified by distillation with CaH_2) was transferred to a Schlenk tube (20 mL). After added MS 4 Å (0.5 g), $Rh_2(OAc)_4$ (4.4 mg, 0.01 mmol), MeOH (2.0 µL), and CH_2Cl_2 (1 mL, purified by distillation with CaH_2), successively, a solution of diazo compound **1** (102 mg, 0.50 mmol) and butyl vinyl ether (100 mg, 1.00 mmol), in CH_2Cl_2 (5 mL, without purification) was added over a period of 1 h using a syringe pump at 23 °C. The syringe was washed with CH_2Cl_2 (1 mL, purified by distillation with CaH_2). After removal of MS 4 Å through Celite, the reaction mixture was filtered through a plug of silica gel (3 cm) with AcOEt/hexane (1:1, 60 mL) as an eluent. The solvent was removed in vacuo, and the residue was purified by column chromatography (94:6 hexane/AcOEt) to provide 67.7 mg (64%) of *endo*-**53a** and *exo*-**53a**. Relative stereochemistry (*endo*/*exo*) of the products **53a**–**c**, **53e** and **f**, **54a**–**58a**, **59**, and **62** could be determined by ^{1}H NMR analysis on the basis of a coupling constant between H-1 and H-7, which reported previously (*exo*:0 Hz).[19]

*4.5.1. 7-exo-Butoxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**53a**).* Colorless viscous oil; $[\alpha]_D^{26}$ +21.2 (c 0.20, $CHCl_3$) (*exo*:*endo*=92:8, 82% ee (*exo*)), IR ($CHCl_3$) 4216, 3447, 3020, 2934, 2402, 2350, 1730, 1682, 1633, 1520, 1454, 1217, 1093, 929, 772, 669 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, J=7.3 Hz), 1.35 (2H, sext, J=7.3 Hz), 1.51 (2H, m), 1.53 (3H, s), 1.81 (1H, ddd, J=2.2, 8.0, 13.4 Hz), 1.87 (1H, m), 2.08 (1H, m), 2.25 (1H, ddd, J=8.3. 9.8, 17.6 Hz), 2.38 (1H, dd, J=7.6, 13.9 Hz), 2.49 (1H, ddt, J=7.8, 17.5, 2.0 Hz), 3.35 (1H, dt, J=6.8, 9.3 Hz), 3.45 (1H, dt, J=6.8, 9.3 Hz), 3.95 (1H, dd, J=2.7, 7.6 Hz), 4.29 (1H, s); ^{13}C NMR ($CDCl_3$) δ 14.0 (CH_3), 19.2 (CH_2), 26.1 (CH_3), 31.7 (CH_2), 34.0 (CH_2), 36.3 (CH_2), 44.0 (CH_2), 69.6 (CH_2), 80.8 (C), 82.8 (CH), 87.4 (CH), 206.2 (C); MS (EI) m/z 212 (M^+), 184, 156, 140, 127, 121, 112, 109, 99, 93, 82, 75, 69, 62, 56, 49, 41, 35, 24, 13. Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50%. Found: C, 67.90, H, 9.47%. The enantiomeric excess was determined by ^{1}H NMR analysis (91:9) after conversion to the corresponding acetals by the reaction with (*R*,*R*)-hydrobenzoin.

*4.5.2. 7-endo-Butoxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (endo-**53a**).* Although *endo*-**53a** could not be separated by chromatography from a mixture with major *exo*-**53a**, it could characterize by ^{1}H NMR. ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, J=7.6 Hz), 1.24–1.33 (2H, m), 1.40 (3H, s), 1.43–1.50 (2H, m), 1.95–2.01 (2H, m), 2.10 (1H, m), 2.23 (1H, dd, J=9.2, 13.4 Hz), 2.44 (1H, ddt, J=7.2, 17.5, 1.5 Hz), 2.65 (1H, ddd, J=8.7, 11.7, 17.0 Hz), 3.35 (2H, dt, J=6.4, 1.9 Hz), 4.31 (2H, m).

*4.5.3. 7-exo-Ethoxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**53b**).* Colorless viscous oil; $[\alpha]_D^{25}$ +40.8 (c 0.94, $CHCl_3$) (*exo*:*endo*=>99:1, 71% ee (*exo*)), IR ($CHCl_3$) 3735, 3649, 3567, 2962, 2873, 2361, 1725, 1541, 1464, 1362, 1260, 1092, 1051, 901, 773, 760, 749 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.21 (3H, t, J=7.0 Hz), 1.51 (3H, s), 1.81 (1H, ddd, J=2.4, 8.4, 13.5 Hz), 1.88 (1H, m), 2.08 (1H, m), 2.25 (1H, ddd, J=8.4, 9.6, 17.6 Hz), 2.39 (1H, dd, J=7.4, 13.8 Hz), 2.49 (1H, ddt, J=7.9, 17.4, 1.8 Hz), 3.42 (1H, dq, J=7.0, 9.1 Hz), 3.52 (1H, dq, J=7.0, 9.1 Hz), 4.00 (1H, dd, J=2.6, 7.4 Hz), 4.30 (1H, s); ^{13}C NMR ($CDCl_3$) δ 15.3 (CH_3), 26.2 (CH_3), 34.1 (CH_2), 36.2 (CH_2), 44.1 (CH_2), 65.1 (CH_2), 80.8 (C), 82.7 (CH), 87.4 (CH), 206.2 (C); MS (EI) m/z 184 (M^+), 169, 156, 138, 127, 111, 93, 81, 70, 54, 38, 26, 15. Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75%. Found: C, 64.94, H, 8.92%. The enantiomeric excess was determined by ^{1}H NMR analysis (85.7:14.3) after conversion to the corresponding acetals by the reaction with (*R*,*R*)-hydrobenzoin.

*4.5.4. 7-exo-Benzyloxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**53c**).* Colorless oil; $[\alpha]_D^{25}$ +36.3 (c 1.00, $CHCl_3$) (*exo*:*endo*=95:5, 60% ee (*exo*)), IR ($CHCl_3$) 3031, 1724, 1453, 1096, 791, 774, 759, 748, 738, 713 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.54 (3H, s), 1.80 (1H, ddd, J=2.5, 8.4, 13.4 Hz), 1.97 (1H, m), 2.08 (1H, m), 2.23 (1H, ddd, J=8.4, 9.8, 18.0 Hz), 2.38 (1H, dd, J=7.4, 13.9 Hz), 2.48 (1H, ddt, J=7.9, 18.0, 2.5 Hz), 4.10 (1H, dd, J=2.6, 7.4 Hz), 4.38 (1H, s), 4.44 (1H, d, J=11.9 Hz), 4.57 (1H, d, J=11.9 Hz), 7.24–7.40 (5H, m); MS (EI) m/z 246 (M^+), 230, 156, 137, 122, 106, 78, 49, 27. Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.15; H, 7.37%. Found: C, 72.96; H, 7.47%. The enantiomeric excess was determined by ^{1}H NMR analysis (80:20) after conversion to the corresponding acetals by the reaction with (R,R)-hydrobenzoin.

*4.5.5. 7-endo-Benzyloxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (endo-**53c**).* Although *endo*-**53c** could not be separated by chromatography from a mixture with major *exo*-**53c**, it could characterize by ^{1}H NMR. ^{1}H NMR ($CDCl_3$) δ 1.40 (3H, s), 1.95–2.16 (3H, m), 2.23 (1H, ddd, J=1.4, 10.4, 13.7 Hz), 2.48 (1H, ddt, J=7.4, 17.6, 1.4 Hz), 2.70 (1H, ddd, J=8.7, 11.5, 17.6 Hz), 4.37 (1H, dd, J=1.2, 7.4 Hz), 4.40 (1H, d, J=11.4 Hz), 4.45 (1H, ddd, J=4.0, 7.4, 10.7 Hz), 4.52 (1H, d, J=11.9 Hz), 7.22–7.38 (5H, m).

*4.5.6. 7-exo-tert-Butoxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**53e**).* Colorless viscous oil; $[\alpha]_D^{25}$ +50.7 (c 1.00, $CHCl_3$) (*exo*:*endo*=95:5, 74% ee (*exo*)), IR ($CHCl_3$) 3426, 2971, 2333, 1720, 1452, 1421, 1366, 1232, 1191, 1145, 1098, 1066, 1039, 861, 843, 776, 721, 706 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.19 (9H, s), 1.52 (3H, s), 1.78 (1H, ddd, J=2.5, 8.0, 13.4 Hz), 1.84 (1H, m), 2.05 (1H, m), 2.29 (1H, ddd, J=8.5, 9.5, 17.8 Hz), 2.40 (1H, dd, J=8.0, 13.4 Hz), 2.46 (1H, ddt, J=7.8, 17.5, 2.0 Hz), 4.15 (1H, s), 4.17 (1H, dd, J=3.2, 7.8 Hz); ^{13}C NMR ($CDCl_3$) δ 26.1 (CH_3), 28.29 (CH_3), 33.9 (CH_2), 36.1 (CH_2), 46.6 (CH_2), 74.6 (C), 75.1 (CH), 80.7 (C), 90.6 (CH), 206.2 (C); MS (EI) m/z 212 (M^+), 167, 157, 149, 138, 127, 121, 112, 109, 97, 91, 84, 77, 69, 57, 37, 26, 13. Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 67.63; H, 9.74. The enantiomeric excess was determined by ^{1}H NMR analysis (87:13) after conversion to the corresponding esters by the reduction with $NaBH_4$ followed by the reaction with (R)-α-methoxyphenylacetic acid.

*4.5.7. 7-endo-tert-Butoxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (endo-**53e**).* Although *endo*-**53e** could not be separated by chromatography from a mixture with major *exo*-**53e**, it could characterize by ^{1}H NMR. ^{1}H NMR ($CDCl_3$) δ 1.13 (9H, s), 1.38 (3H, s), 1.91 (1H, dd, J=3.9, 13.2 Hz), 1.97 (1H, m), 2.07 (1H, m), 2.22 (1H, ddd, J=1.2, 10.4, 13.2 Hz), 2.40 (1H, ddt, J=7.0, 17.0, 1.7 Hz), 2.68 (1H, ddd, J=8.5, 11.7, 17.1 Hz), 4.11 (1H, dd, J=1.2, 7.1 Hz), 4.48 (1H, ddd, J=3.9, 7.1, 10.4 Hz).

*4.5.8. 7-exo-Cyclohexyloxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**53f**).* Pale yellow oil; $[\alpha]_D^{25}$ +28.3 (c 1.00, $CHCl_3$) (*exo*:*endo*=89:11, 73% ee (*exo*)), IR ($CHCl_3$) 3424, 3030, 2928, 2362, 1728, 1496, 1453, 1371, 1256, 1200, 1103, 1030, 924, 891, 701 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.10–1.93 (10H, m), 1.53 (3H, s), 1.80 (1H, ddd, J=2.4, 8.3, 13.4 Hz), 1.88 (1H, m), 2.07 (1H, m), 2.25 (1H, ddd, J=8.3, 9.7, 18.0 Hz), 2.38 (1H, dd, J=7.6, 13.7 Hz), 2.47 (1H, ddt, J=7.8, 17.6, 2.2 Hz), 3.26 (1H, m), 4.15 (1H, dd, J=2.9, 7.5 Hz), 4.25 (1H, s); ^{13}C NMR ($CDCl_3$) δ 24.1 (CH_2), 24.2 (CH_2), 25.6 (CH_2), 26.0 (CH_3), 32.1 (CH_2), 32.8 (CH_2), 34.0 (CH_2), 36.2 (CH_2), 44.7 (CH_2), 76.9 (CH), 79.8 (CH), 80.6 (C), 88.8 (CH), 206.2 (C); MS (EI) m/z 238 (M^+), 225, 211, 197, 173, 157, 141, 127, 114, 83, 70, 57, 41, 26, 13. Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.56; H, 9.30%. Found: C, 70.55; H, 9.33%. The enantiomeric excess was determined by ^{1}H NMR analysis (86.6:13.4) after conversion to the corresponding acetals by the reaction with (R,R)-hydrobenzoin.

*4.5.9. 7-endo-Cyclohexyloxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (endo-**53f**).* Although *endo*-**53f** could not be separated by chromatography from a mixture with major *exo*-**53f**, it could characterize by ^{1}H NMR. ^{1}H NMR ($CDCl_3$) δ 1.09–1.98 (10H, m), 1.38 (3H, s), 1.98 (2H, m), 2.08 (1H, m), 2.23 (1H, ddd, J=1.5, 13.4, 10.5 Hz), 2.43 (1H, ddt, J=7.3, 17.0, 1.5 Hz), 2.68 (1H, ddd, J=8.5, 11.7, 17.0 Hz), 3.25 (1H, m), 4.24 (1H, dd, J=1.5, 6.8 Hz), 4.48 (1H, ddd, J=4.1, 6.8, 10.5 Hz).

*4.5.10. 7-exo-(tert-Butyldimethylsilyl)oxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**59**).* Colorless oil; $[\alpha]_D^{25}$ +28.1 (c 1.00, $CHCl_3$) (*exo*:*endo*=> 99:1, 82% ee (*exo*)), IR ($CHCl_3$) 3735, 3649, 2932, 2361, 1717, 1541, 1457, 1215, 1082, 837, 791, 775, 760, 747, 738, 721 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.07 (3H, s), 0.08 (3H, s), 0.88 (9H, s), 1.53 (3H, s), 1.78 (1H, ddd, J=2.2, 8.3, 13.4 Hz), 1.82 (1H, m), 2.05 (1H, m), 2.24 (1H, ddd, J=8.3, 9.8, 18.8 Hz), 2.40 (1H, dd, J=7.3, 13.6 Hz), 2.47 (1H, ddt, J=7.8, 17.6, 2.1 Hz), 4.12 (1H, s), 4.38 (1H, dd, J=2.4, 7,3 Hz); ^{13}C NMR ($CDCl_3$) δ −4.6 (CH_3), −4.5 (CH_3), 18.2 (C), 25.9 (CH_3), 26.2 (CH_3), 34.1 (CH_2), 36.3 (CH_2), 47.4 (CH_2), 75.9 (CH), 81.3 (C), 91.3 (CH), 206.2 (C); MS (EI) m/z 270 (M^+), 255, 237, 213, 195, 165, 149, 131, 117, 97, 75, 57, 41, 27. Anal. Calcd for $C_{14}H_{26}O_3Si$: C, 62.18; H, 9.69%. Found: C, 62.16; H, 9.87%. The enantiomeric excess was determined by ^{1}H NMR analysis (91:9) after conversion to the corresponding esters by the reduction with $NaBH_4$ followed by the reaction with (R)-α-methoxyphenylacetic acid.

*4.5.11. 7-exo-Butoxy-5-ethyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**54a**).* Colorless viscous oil; $[\alpha]_D^{20}$ −16.6 (c 1.00, $CHCl_3$) (*exo*:*endo*=>99:1, 79% ee (*exo*)), IR ($CHCl_3$) 3735, 3649, 3567, 2962, 2873, 2361, 1725, 1541, 1464, 1362, 1260, 1092, 1051, 901, 773, 760, 749 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, J=7.5 Hz), 1.36 (2H, sext, J=7.5 Hz), 1.55 (2H, m), 1.75–1.91 (4H, m), 2.04 (1H, m), 2.23 (1H, dd, J=7.5, 13.6 Hz), 2.26 (1H, m), 2.51 (1H, ddt, J=8.1, 17.6, 2.2 Hz), 3.36 (1H, m), 3.44 (1H, m), 3.98 (1H, dd, J=2.4, 7.3 Hz), 4.28 (1H, s); ^{13}C NMR ($CDCl_3$) δ 9.0 (CH_3), 14.0 (CH_3), 19.4 (CH_2), 31.7 (CH_2), 32.3 (CH_2), 33.6 (CH_2), 33,9 (CH_2), 41.8 (CH_2), 69.4 (CH_2), 82.3 (CH), 83.5 (C), 87.2 (CH), 206.2 (C); MS (EI) m/z 226 (M^+), 223, 213, 185, 171, 154, 141, 126, 113, 85, 69, 54, 41, 27. Anal. Calcd for $C_{13}H_{22}O_3$: C, 68.99; H, 9.80%. Found: C, 68.73; H, 9.73%. The enantiomeric excess was determined by ^{1}H NMR analysis (89.5:10.5) after conversion to the corresponding acetals by the reaction with (R,R)-hydrobenzoin.

*4.5.12. 7-exo-Butoxy-5-isopropyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**55a**).* Colorless viscous oil; $[\alpha]_D^{25}$ +5.62 (c 1.00, $CHCl_3$) (*exo*:*endo*=> 99:1, 84% ee (*exo*)), IR ($CHCl_3$) 2963, 2875, 1724, 1468, 1370, 1232, 1094, 1055, 904, 789, 759, 752, 741, 717 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, J=7.6 Hz), 0.98 (3H, d, J=7.1 Hz), 1.08 (3H, d, J=6.8 Hz), 1.36 (2H, m), 1.54 (2H, m), 1.73 (1H, ddd, J=3.5, 8.0, 13.2 Hz), 1.87 (1H, m), 2.06 (2H, m), 2.22 (2H, m), 2.51 (1H, dddd, J=1.5, 3.5, 8.3, 17.4 Hz), 3.35 (1H, m), 3.43 (1H, m), 3.96 (1H, dd, J=2.4, 7.3 Hz), 4.30 (1H, s); ^{13}C NMR ($CDCl_3$) δ 13.9 (CH_3), 17.7 (CH_3), 17.8 (CH_3), 19.3 (CH_2), 30.1 (CH_2), 31.7 (CH_2), 33.9 (CH_2), 36,4 (CH), 40.9 (CH_2), 69.3 (CH_2), 82.1 (CH), 85.7 (C), 87.1 (CH), 207.5 (C); MS (EI) m/z 240 (M^+), 227, 213, 197, 184, 171, 157, 141, 125, 113, 96, 82, 67, 53, 40, 26, 13. Anal. Calcd for $C_{14}H_{24}O_3$: C, 69.96; H, 10.07%. Found: C, 69.79; H, 10.19%. The enantiomeric excess was determined by ^{1}H NMR analysis (92:8) after conversion to the corresponding acetals by the reaction with (R,R)-hydrobenzoin.

*4.5.13. 7-exo-Butoxy-5-tert-butyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**56a**).* Colorless viscous oil; $[\alpha]_D^{20}$ −13.6 (c 0.31, $CHCl_3$) (*exo*:*endo*=> 99:1, 82% ee (*exo*)), IR ($CHCl_3$) 2963, 2874, 1726, 1474, 1368, 1119, 790, 775, 760, 746, 722 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, J=7.6 Hz), 1.03 (9H, s), 1.36 (2H, sext, J=7.6 Hz), 1.54 (2H, m), 1.69 (1H, m), 2.02 (1H, dd, J=7.3, 13.9 Hz), 2.14 (1H, dd, J=2.2, 13.9 Hz), 2.28 (2H, m), 2.51 (1H, m), 3.35 (1H, m), 3.41 (1H, m), 3.93 (1H, dd, J=2.2, 7.3 Hz), 4.28 (1H, s); ^{13}C NMR ($CDCl_3$) δ 14.0 (CH_3), 19.4 (CH_2), 25.7 (CH_3), 29.7 (CH_2), 31.8 (CH_2), 34.3 (CH_2), 36,0 (C), 38.8 (CH_2), 69.1 (CH_2), 82.0 (CH), 87.2 (CH), 87.6 (C), 208.1 (C); MS (EI) m/z 254 (M^+), 239, 221, 197, 183, 169, 152, 141, 137, 123, 109, 97, 83, 71, 55, 37, 24, 12. Anal. Calcd for $C_{15}H_{26}O_3$: C, 70.83; H, 10.30%. Found: C, 70.58; H, 10.49%. The enantiomeric excess was determined by ^{1}H NMR analysis (91:9) after conversion to the corresponding acetals by the reaction with (*R*,*R*)-hydrobenzoin.

*4.5.14. 7-exo-Butoxy-5-benzyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**57a**).* Colorless viscous oil; $[\alpha]_D^{20}$ −4.00 (*c* 0.30, $CHCl_3$) (*exo*:*endo*=98:2, 75% ee (*exo*)), IR ($CHCl_3$) 3424, 3030, 2928, 2362, 1728, 1496, 1453, 1371, 1256, 1200, 1103, 1030, 924, 891, 701 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.91 (3H, t, *J*=6.8 Hz), 1.33 (2H, m), 1.53 (2H, m), 1.70 (1H, ddd, *J*=2.2, 8.1, 12.9 Hz), 2.02 (2H, m), 2.18 (1H, ddd, *J*=7.9, 9.6, 17.6 Hz), 2.27 (1H, dd, *J*=7.6, 13.9 Hz), 2.43 (1H, ddt, *J*=2.2, 8.1, 17.6 Hz), 3.10 (1H, d, *J*=13.7 Hz), 3.13 (1H, d, *J*=13.7 Hz), 3.32 (1H, m), 3.41 (1H, m), 3.97 (1H, dd, *J*=2.7, 7.6 Hz), 4.34 (1H, s), 7.21–7.32 (5H, m); ^{13}C NMR ($CDCl_3$) δ 14.0 (CH_3), 19.4 (CH_2), 31.8 (CH_2), 33.8 (CH_2), 33.9 (CH_2), 42.7 (CH_2), 45.7 (CH_2), 69.8 (CH_2), 82.3 (C), 83.2 (CH), 87.4 (CH), 126.6 (CH), 128.1 (CH), 130.0 (CH), 136.7 (C), 206.2 (C); MS (EI) *m*/*z* 280 (M$^+$) 270, 231, 216, 205, 197, 186, 169, 157, 142, 131, 123, 115, 105, 91, 81, 67, 53, 37, 26, 16. Anal. Calcd for $C_{18}H_{24}O_3$: C, 74.97; H, 8.39%. Found: C, 74.80; H, 8.40%. The enantiomeric excess of the adduct was determined by HPLC analysis (DAICEL Chiralpak OD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=27.0 min (major), 36.0 min (minor).

*4.5.15. 7-exo-Butoxy-5-phenyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**58a**).* Colorless viscous oil; $[\alpha]_D^{20}$ −9.00 (*c* 0.52, $CHCl_3$) (*exo*:*endo*=>99:1, 78% ee (*exo*)), IR ($CHCl_3$) 3010, 2960, 2873, 1727, 1496, 1449, 1361, 1233, 1119, 1090, 1046, 909, 773, 759 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.89 (3H, t, *J*=7.3 Hz), 1.34 (2H, sext, *J*=7.3 Hz), 1.52 (2H, m), 2.16–2.34 (4H, m), 2.41 (1H, ddd, *J*=8.5, 9.5, 17.5 Hz), 2.58 (1H, ddt, *J*=2.4, 7.3, 17.5 Hz), 2.79 (1H, dd, *J*=7.1, 13.7 Hz), 3.36 (1H, m), 3.45 (1H, m), 4.10 (1H, dd, *J*=2.4, 7.5 Hz), 4.49 (1H, s); ^{13}C NMR ($CDCl_3$) δ 13.9 (CH_3), 19.4 (CH_2), 31.6 (CH_2), 34.2 (CH_2), 37.6 (CH_2), 44.7 (CH_2), 69.5 (CH_2), 82.1 (C), 84.0 (CH), 87.5 (CH), 124.4 (CH), 127.0 (CH), 128.2 (CH), 144.2 (C), 205.6 (C); MS (EI) *m*/*z* 274 (M$^+$), 245, 203, 174, 146, 118, 109, 77, 60, 39. Anal. Calcd for $C_{17}H_{22}O_3$: C, 74.42; H, 8.08%. Found: C, 74.33; H, 8.15%. The enantiomeric excess of the adduct was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=96.0 min (minor), 185.0 min (major).

*4.5.16. 5,7-Dimethyl-7-methoxy-8-oxabicyclo[3.2.1]octan-2-one (**60**).* Colorless viscous oil; $[\alpha]_D^{25}$ +26.7 (*c* 0.10, $CHCl_3$) (81:19, mixture of diastereomer, 22% ee (major)), IR ($CHCl_3$) 3735, 2976, 1727, 1455, 1380, 1313, 1259, 1233, 1194, 1147, 1072, 858, 772, 758, 748, 722 cm^{-1}; ^{1}H NMR ($CDCl_3$) Major: δ 1.41 (3H, s), 1.48 (3H, s), 1.81 (1H, d, *J*=13.1 Hz), 1.94 (1H, dd, *J*=8.7, 13.3 Hz), 2.07 (1H, m), 2.27 (1H, d, *J*=13.1 Hz), 2.44 (1H, ddt, *J*=7.3, 17.3, 2.9 Hz), 2.69 (1H, ddd, *J*=8.5, 11.4, 17.3 Hz), 3.22 (3H, s), 3.87 (1H, s); ^{13}C NMR ($CDCl_3$) Major: δ 24.8 (CH_3), 26.9 (CH_3), 34.1 (CH_2), 37.6 (CH_2), 47.7 (CH_2), 52.4 (CH_3), 81.0 (C), 85.2 (C), 89.9 (CH), 205.6 (C); MS (EI) *m*/*z* 184 (M$^+$), 155, 143, 124, 113, 99, 85, 73, 55, 43, 27, 15. Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75%. Found: C, 65.15; H, 8.73%. The enantiomeric excess was determined by ^{1}H NMR analysis (61:39) after conversion to the corresponding acetals by the reaction with (*R*,*R*)-hydrobenzoin.

*4.5.17. 7-Butoxy-7-(tert-butyldimethylsilyl)oxy-5-methyl-8-oxabicyclo[3.2.1]octan-2-one (**61**).* Colorless viscous oil; $[\alpha]_D^{25}$ +2.75 (*c* 1.00, $CHCl_3$) (63:37, mixture of diastereomer), IR ($CHCl_3$) 2959, 2933, 2860, 1727, 1464, 1412, 1381, 1362, 1308, 1254, 1173, 1135, 1045, 790, 749, 728 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.14 (3H×63/100, s, Major), 0.16 (3H×63/100, s, Major), 0.18 (3H×37/100, s, Minor), 0.19 (3H×37/100, s, Minor), 0.84 (9H, s), 0.92 (3H, t, *J*=7.3 Hz), 1.21–1.60 (6H, m), 1.44 (3H×37/100, s, Minor), 1.45 (3H×63/100, s, Major), 1.92 (1H, m), 2.09 (1H, m), 2.43 (1H, m), 2.60 (1H, m), 3.48 (2H, m), 4.05 (1H×37/100, s), 4.19 (1H×63/100, s); ^{13}C NMR ($CDCl_3$) Major: δ −3.3 (CH_3), −3.0 (CH_3), 14.1 (CH_3), 18.1 (C), 19.4 (CH_2), 25.8 (CH_3), 26.5 (CH_3), 32.1 (CH_2), 33.6 (CH_2), 37.3 (CH_2), 49.7 (CH_2), 63.1 (CH_2), 80.4 (C), 85.5 (CH), 108.6 (C), 203.7 (C); Minor: δ −3.0 (CH_3), −2.8 (CH_3), 14.1 (CH_3), 18.4 (C), 19.4 (CH_2), 25.8 (CH_3), 26.7 (CH_3), 31.9 (CH_2), 33.6 (CH_2), 37.7 (CH_2), 49.2 (CH_2), 63.7 (CH_2), 80.7 (C), 90.1 (CH), 109.1 (C), 203.9 (C); MS (EI) *m*/*z* 342 (M$^+$), 287, 269, 243, 213, 184, 154, 131, 113, 93, 74, 46, 27. Anal. Calcd for $C_{18}H_{34}O_4Si$: C, 63.11; H, 10.00%. Found: C, 62.91; H, 10.14%.

*4.5.18. 5-Methyl-7-exo-phenyl-8-oxabicyclo[3.2.1]octan-2-one (exo-**62**).* Colorless viscous oil; $[\alpha]_D^{20}$ +29.9 (*c* 0.23, $CHCl_3$) (*exo*:*endo*=>99:1, 80% ee (*exo*)), IR ($CHCl_3$) 2970, 1724, 1034, 856, 540 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.56 (3H, s), 1.97 (1H, dd, *J*=4.4, 13.4 Hz), 1.98 (1H, m), 2.15 (1H, m), 2.48 (1H, ddt, *J*=8.1, 17.5, 2.0 Hz), 2.63 (1H, dd, *J*=9.8, 13.4 Hz), 3.35 (1H, dd, *J*=4.4, 9.8 Hz), 4.23 (1H, s), 7.19–7.32 (5H, m); ^{13}C NMR ($CDCl_3$) δ 25.9 (CH_3), 32.9 (CH_2), 37.1 (CH_2), 45.7 (CH_2), 48.9 (CH), 81.4 (C), 89.7 (CH), 126.5 (CH), 126.6 (CH), 128.6 (CH), 145.2 (C), 206.3 (C); MS (EI) *m*/*z* 216 (M$^+$), 188, 167, 149, 131, 104, 79, 65, 42, 27. Anal. Calcd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46%. Found: C, 77.77; H, 7.38%. The enantiomeric excess of the adduct was determined by HPLC analysis (DAICEL Chiralpak AD-H, 1:99 *i*-PrOH/hexane, flow 0.5 mL/min, 35 °C) t_R=80.0 min (minor), 157.0 min (major).

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Supplementary data

General methods and materials for additional experimental section, additional experimental procedures, and ^{1}H and ^{13}C NMR spectra of the products (PDF). Supplementary data associated with this article can be found in online version, at doi:10.1016/j.tet.2010.01.095.

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12. Absolute configuration of the cycloadduct was not determined.
13. The *endo*-adduct is defined as the product in which the more important substituent is on the opposite side of the epoxy bridge, whereas the *exo*-adduct indicates the product in which the more important substituent is on the same side as the epoxy bridge.
14. $La(OTf)_3$: quant yield, 52% ee; $Sm(OTf)_3$: 86% yield, 55% ee; $Gd(OTf)_3$: 69% yield, 60% ee; $Tb(OTf)_3$: 60% yield, 61% ee; $Er(OTf)_3$: 74% yield, 59% ee; $Tm(OTf)_3$: quant yield, 64% ee; $Lu(OTf)_3$: 88% yield, 55% ee.
15. (4*S*,5*S*)-Pybox-Ph_2–$Eu(OTf)_3$ (10 mol %), CH_2Cl_2, reflux: 89% yield, 44% ee; (4*S*,5*S*)-Pybox-Ph_2–$Yb(OTf)_3$ (10 mol %), $CHCl_3$, reflux: 71% yield, 45% ee.
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17. Although the reason for the switch of the diastereoselectivity in this reaction is not clear at this point, flat structure of the carbonyl ylide for 2-benzopyryrium-4-olates may influence the *endo*/*exo* selectivity by inhibition of steric hindrance with vinyl esters. PM3 calculations (heat of formation) of **3f** and **28f** show that *exo*-cycloadducts are thermodynamically more stable than *endo*-cycloadducts, and *endo*-**53a** is slightly more stable (0.81 kcal/mol) than the corresponding *exo*-adduct.
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27. The reason for the improvement of enantioselectivity by the addition of basic inorganic salts is not clear at this point. Considering the reactivity of allyl alcohol compared with allyl butyl ether in the presence of (4*S*,5*S*)-Pybox-Ph_2–lanthanoid metal complexes, however, the role of the catalyst is probably not only activation of the carbonyl ylide by coordination but also bring the reactants including allyl alcohol close together to achieve the appropriate transition state. The addition of basic inorganic salts may be attributed to the favored coordination of allyl alcohol to the catalyst by hydrogen bonding of allyl alcohol.