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Rhodium(II)-catalyzed olefin cyclopropanation with the phenyliodonium ylide derived from Meldrum's acid

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Abstract—The phenyliodonium ylide **3a** derived from Meldrum's acid reacts with olefins in the presence of Rh(II) carboxylate catalysts to afford cyclopropanes. The reaction is stereospecific. Enantioselectivities of up to 63% have been observed for the cyclopropanation of pent-1-ene. No 1,3-cycloadducts are formed between **3a** and polarized olefins such as furan or 2,3-dihydrofuran.

1. Introduction

Phenyliodonium ylides[1] are potential substitutes for diazo compounds[2] in transition metal-catalyzed carbenoid reactions.[3] We have recently shown that the Rh(II)-catalyzed cyclopropanation and CH bond insertion using phenyliodonium ylides proceeds indeed via metal carbene intermediates.[4] Metal carbenes are also involved in the Cu(I)-catalyzed decomposition of phenyliodonium ylides.[5] However, in the case of intramolecular cyclopropanations an uncatalyzed pathway may compete with the Rh(II)- or Cu(I)-catalyzed carbene transfer.[6,7]

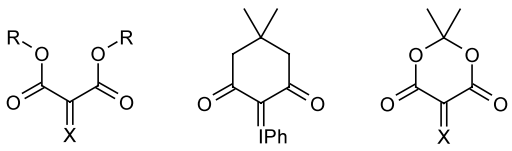
Phenyliodonium ylides occur usually as amorphous, polymeric solids or oils. In order to be isolable, they must carry two electron-attracting substituents, such as carbonyl, carboxyl, cyano, or sulfonyl groups.[8] Phenyliodonium ylides derived from malonate esters such as **1a**[4,5,7] and acyclic 1,3-diketones are unstable and, therefore, difficult to purify, while those derived from cyclic 1,3-dicarbonyl compounds such as **2** or **3a** are quite convenient to handle (Scheme 1).[9]

This report deals with the transition metal-catalyzed cyclopropanation of olefins with the ylide **3a**, derived from Meldrum's acid **3c**, as a synthetic equivalent of diazomalonate ester or the corresponding phenyliodonium ylides **1**. Our interest in this ylide originated from the unsatisfactory results reported for the Rh(II)-catalyzed asymmetric cyclopropanation of styrenes with diazo-malonate ester. Diazomalonates are not decomposed with Rh(II) carboxamidate-catalysts such as $[Rh_2\{(2S)\text{-mepy}\}_4]$ even at elevated temperatures, except with $[Rh_2\{(4S)\text{-meaz}\}_4]$, which reacts in refluxing dichloromethane. However, the highest reported ee (for 4-trifluoromethyl-styrene) is only 50%.[10] The known high reactivity of phenyliodonium ylides[7] was expected to allow the screening of a larger variety of catalysts with **3a** than with diazo malonate (**1b**) and to work under milder conditions.

2. Results and discussion

2.1. Olefin cyclopropanation with ylide 3a

The ylide **3a** was prepared from Meldrum's acid (2,2-dimethyl-1,3-dioxane-4,6-dione, **3c**) and $PhI(OAc)_2$ according to Schank and Lick.[11] It was stable in CH_2Cl_2 solution in the absence of catalyst. Although it is reportedly only moderately reactive towards Cu-catalysts,[12] it decomposed in CH_2Cl_2 at room temperature



1a X = IPh
1b X = N_2

2

3a X = IPh
3b X = N_2
3c X = H_2

Scheme 1.

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in the presence of $[Rh_2(OAc)_4]$ to iodobenzene (**4**, 100%), Meldrum's acid **3c** (33%) and acetone (ca. 5%). No other decomposition products, carbene dimer,[13] nor products derived from reaction of the intermediate carbene with solvent could be isolated or characterized. These observations parallel those of DeLuca et al. for thermal and photochemical decomposition of **3a**, who, in addition, reported formation of an as yet unidentified C_3O_3 compound.[14] Thermal decomposition of **3b**, in turn, reportedly affords N_2, CO, acetone and small amounts of propene and C_3O_2.[15] Carbene dimers are however typically observed upon metal-catalyzed decomposition of **1a**.[4,12,16]

In the presence of an olefin, the decomposition of the metallocarbene derived from **3a** competes with intermolecular cyclopropanation, and an excess of olefin is required to reach satisfactory yields. The dependence of the yield of cyclopropane upon the olefin concentration in the $[Rh_2(OAc)_4]$-catalyzed cyclopropanation of styrene **5a** was investigated with CH_2Cl_2 as solvent at room temperature (Table 1). The yield of cyclopropane **6a**[17] and iodobenzene **4** was determined by GC, using an internal standard (dodecane). Acceptable yields of cyclopropane required a significant excess of olefin (ca. 5–10-fold). The lowest yield resulted when equimolar amounts of **3a** and **5a** were used. On the other hand, the cyclopropane yield (calculated with respect to the limiting reagent) increased again when **3a** was used in excess. Surprisingly, when $[Rh_2(OAc)]_4$ was replaced by $[Rh_2\{(S)\text{-nttl}\}_4]$ the yields increased slightly, but reproducibly, for example from 81 to 97% with a 2:1 ratio of **3a** over styrene. Addition of iodobenzene (1.0 equiv.) reduced the reaction rate, but had no significant effect on the yield of **6a**. In contrast, the decomposition of the corresponding diazo compound **3b** did not proceed at all under these reaction conditions, but required heating in fluorobenzene to 80–90°C to afford comparable yields of **6a**.

A series of olefins was subjected to cyclopropanation with **3a** under standard conditions (see Section 4). The results are summarized in Table 2. Yields refer to isolated cyclopropanes after purification by flash chromatography (SiO_2, neutralized with Et_3N) or recrystallization. In general, the reactions were very clean, and no secondary products could be detected except iodobenzene (Scheme 2).

Table 1. $[Rh_2(OAc)_4]$-catalyzed cyclopropanation of styrene **5a** with **3a**[a]

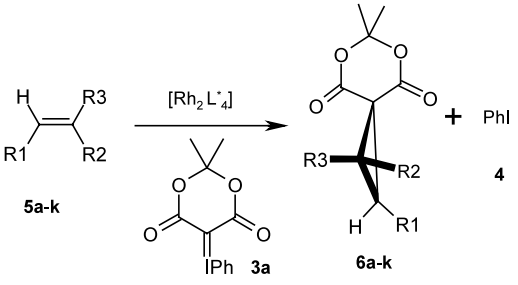
Run	Excess **5a**	Yield of **6a** (%)
1	10	100
2	8	79
3	5	85
4	2	29
5	1.0	36
6	0.5	56[b]

[a] With 5% of $[Rh_2(OAc)_4]$ in CH_2Cl_2 at rt.
[b] With respect to **5a**.

Table 2. Cyclopropanation of olefins **5** with **3a**[a]

Entry	Olefin **5**			Yield of **6**[b] (%)
	R^1	R^2	R^3	
a	Ph	H	H	81
b	PrPr	H	H	87
c	Me_3C	H	H	42
d	H	c-CH=CHCH$_3$	H	45
e	OAc	H	H	40[c]
f		-$(CH_2)_4$-	H	73
g		-O-CH=CH-	H	0
h		-O-CH_2CH_2	H	0
i	Me	Et	H	75
j	Me	H	Et	69
k	Ph	H	Me	39
l	Me	Et	Me	73

[a] Standard conditions, see Section 4.
[b] Isolated yield.
[c] Crude yield 80%.



Scheme 2.

The cyclopropanes **6** were isolated in good to excellent yield even with polar olefins such as vinyl acetate **5e**. This is remarkable, because the diazo compounds or ylides derived from cyclohexane-1,3-dione or dimedone, such as **2a**[18] react with polar olefins via 1,3-dipolar cycloaddition rather than by cyclopropanation.[19] However, no characterizable products could be isolated upon reaction of **3a** with furan **5g** or dihydrofuran **5f**. The stereospecificity of the cyclopropanation was examined with *cis*- and *trans*-pent-2-ene. The (*Z*)-isomer **5i** afforded exclusively *cis*-cyclopropane **6i** and only *trans*-**6j** resulted from reaction of (*E*)-**5j**. Since the vicinal coupling constants of the cyclopropane protons of **6i** and **6j** were almost identical, the *cis*-configuration of **6i** was established by NOESY experiments which showed interactions between the methylene group of the ester and the *cis*-methyl substituent of the cyclopropane, as well as between the vicinal protons of the cyclopropane ring. No exploitable NOE effect was present in the spectra of the *trans* isomer **6j**, however. Another characteristic feature of the stereoisomers was found in the ^{13}C NMR: In the *trans* isomer **6j**, the carbonyl carbons resonated almost at the same field (167.0 and 166.8 ppm), while the CO-resonances of the *cis*-isomer **6i** were well separated (168.4 and 163.7 ppm). The stereospecificity of the cyclopropanation is consistent with a typical carbene mechanism, as established for olefin cyclopropanation with diazo compounds.[1] This contrasts with the intramolecular cyclopropanation of

phenyliodonium ylides, where a competing uncatalyzed and stepwise pathway involving radical or carbenium ion intermediates has been observed.[5] Apparently, this pathway, which is detrimental for the enantioselectivity in the intramolecular cyclopropanation of ylides, does not occur in the intermolecular version.

Some chiral Rh(II) catalysts were examined under standard conditions (CH_2Cl_2, 20°C) with styrene **5a** and pentene **5b** as substrates (Table 3, Scheme 3). The enantiomeric excess was determined by HPLC for **6a**, and by GC for **6b**. Although rhodium carboxamidates were efficient for ylide decomposition, the catalysts showed no induction. Similarly, the proline-derived rhodium carboxylates produced no enantioselectivity. Encouraging results were obtained, however, with the Ikegami type catalysts, based on phthaloyl-derived amino acids. A newly designed catalyst using the 1,8-naphthalimide of *tert*-leucine, [Rh_2{(*S*)-nttl}$_4$] was still more effective and gave ees of 63% for pentene and 37% for styrene, respectively. This compares favorably with the highest ee of 44% so far reported for cyclopropanation of styrene with diazo malonate in the presence of [Rh_2{(4*S*)-bnaz}$_4$] (50% for 4-trifluoromethylstyrene).[10] Some asymmetric cyclopropanations were also carried out with vinylacetate **5e** as substrate; however the resulting cyclopropane **6e** racemized slowly upon standing.

The selectivity of the metallocarbene derived from the ylide **3a** differs remarkably from that derived from **2** or from the corresponding diazo compound, which reacts with olefins preferentially via formal 1,3-cycloaddition,[19,20] while cyclopropanation seems to be the exception. The cyclopropanation of styrene with diazodimedone has been reported to proceed with >90% ee in the presence of a chiral Cu(I)-catalyst.[21] However, this remarkable result has never been confirmed.[2a] We are currently re-investigating the transition metal-catalyzed cyclopropanation and cycloaddition of diazodimedone and the corresponding phenyliodonium ylide.

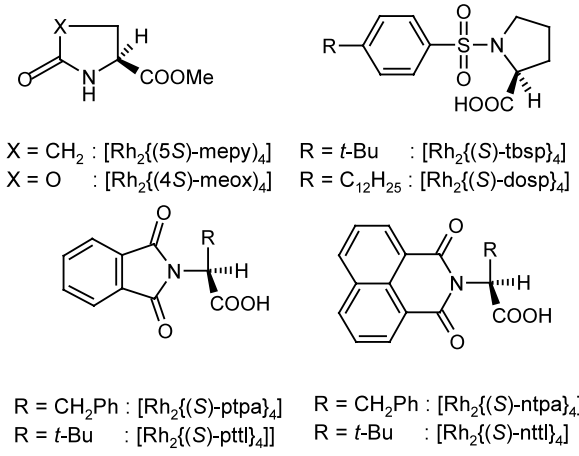
The abs. configuration of the spirocyclopropane **6a** derived from styrene with [Rh_2{(*S*)-nttl}$_4$] ([α]$_D^{22}$ +68.6, *c* 0.87, $CHCl_3$ for 36% ee) was determined via its conversion to the dimethyl malonate **7a** via partial hydrolysis (KOH/MeOH),[12] followed by treatment of the resulting diastereomeric mixture of monoesters **7a** with trimethylsilyl diazomethane (Scheme 4). The diester **8a** had [α]$_D^{22}$ +44.5 (*c* 1.1, PhH for 26% ee, by GC), from which the *R*-configuration of the major isomer was deduced. Authentic (*S*)-**8a** has [α]$_D^{23}$ −137.2 (*c* 1.2, PhH).[22]

The spirocyclopropane **6b** obtained from pentene in the presence of [Rh_2{(*S*)-nttl}$_4$] ([α]$_D^{22}$ +5.9, *c* 1.2, $CHCl_3$ for 59% ee) was hydrolyzed to a *cis*/*trans* mixture of mono-

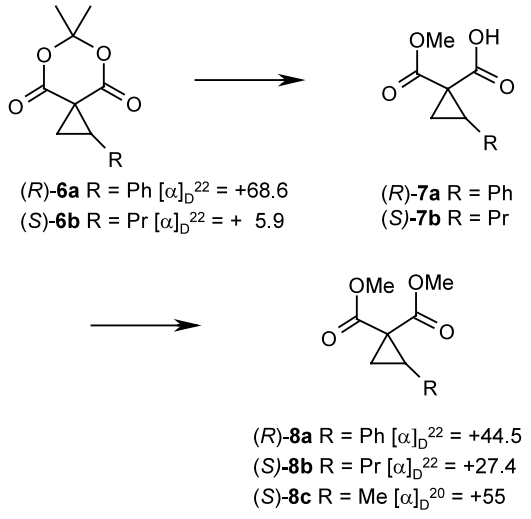
Table 3. Enantioselective cyclopropanation of styrene **5a** and pent-1-ene **5b** with Rh(II)-catalysts[a]

Olef	Catalyst	Yield (%)	Ee (%)	Comment[b]
5a	[Rh_2{(*S*)-pttl}$_4$]	75	40	(*R*)
5a	[Rh_2{(*S*)-nttl}$_4$]	84	37	(*R*)
5b	[Rh_2{(5*S*)-mepy}$_4$]	80	0	
5b	[Rh_2{(4*S*)-meox}$_4$]	96	0	
5b	[Rh_2{(*S*)-dosp}$_4$]	95	0	
5b	[Rh_2{(*S*)-tbsp}$_4$]	82	3	
5b	[Rh_2{(*S*)-ptpa}$_4$]	95	22	(*S*)
5b	[Rh_2{(*S*)-pttl}$_4$]	100	48	(*S*)
5b	[Rh_2{(*S*)-ntpa}$_4$]	96	26	(*S*)
5b	[Rh_2{(*S*)-nttl}$_4$]	97	59	(*S*)
5b	[Rh_2{(*S*)-nttl}$_4$]	60	48	in pentane
5b	[Rh_2{(*S*)-nttl}$_4$]	93	63	$0<T<5$°C
5b	[Rh_2{(*S*)-nttl}$_4$]	90	61	−17°C

[a] In CH_2Cl_2, standard conditions, see Section 4. Yield determined by GC and NMR.
[b] Abs. configuration of predominant enantiomer.



Scheme 3. Ligands and abbreviations of Rh(II)-catalysts.

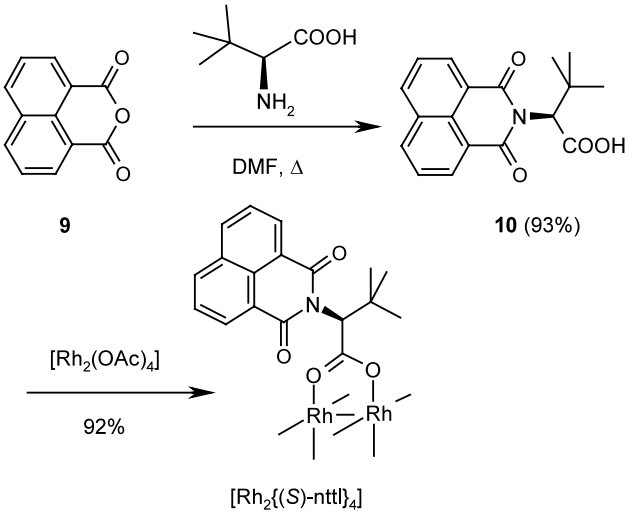


Scheme 4.

esters **7b** ($[\alpha]_D^{22}$ −15.6, 60% de). The diester **8b** obtained after treatment with trimethylsilyldiazomethane[23] had $[\alpha]_D^{22}$ +27.4 (*c* 1.1, $CHCl_3$, for 58% ee). The (*S*)-configuration is assigned to **8b** upon comparison of the specific rotation with that of authentic dimethyl (*S*)-2-methylcyclopropane-1,1-dicarboxylate ($[\alpha]_D^{20}$ +55).[24] Although the CIP rules attribute different absolute configuration, the orientation in space of the substituents of **6a** and **6b** is identical.

2.2. Synthesis of $[Rh_2\{(S)\text{-nttl}\}_4]$

(*S*)-*N*-Naphthoyl-*tert*-leucine **10** was prepared via condensation of 1,8-naphthalic anhydride **9** and L-*tert*-leucine (Scheme 5).[25] Ligand exchange was carried out by refluxing $[Rh_2(OAc)_4]$ with a 10-fold excess of **10** in chlorobenzene for 24 h, by continuously absorbing the resulting acetic acid in a Soxhlet extractor containing anhydrous Na_2CO_3 and sand. $[Rh_2\{(S)\text{-nttl}\}_4]$ was isolated in an overall yield of 85%.



Scheme 5.

3. Conclusion

The ylide **3a** derived from Meldrum's acid is a useful synthetic equivalent of ylides derived from malonic esters **1a** and of diazo compounds **1b** and **3b**. It reacts under mild conditions in the presence of Rh(II)-catalysts to afford cyclopropanes in good yields and with enantioselectivities of up to 63%.

4. Experimental

4.1. General

See Ref. 26.

4.2. Synthesis of 2-phenyliodonio-5,5-dimethyl-4,6-dioxa-1,3-dioxocyclohexane methylide 3a[8]

To Meldrum's acid (2,2-dimethyl-1,3-dioxan-4,6-dione, 1.44 g, 10.0 mmol) in 10% aq. Na_2CO_3 (30 mL) was added, at 25°C, diacetoxyiodobenzene (3.22 g, 10.0 mmol) in EtOH (40 mL). After stirring overnight, the mixture was poured on ice-water (75 mL). After extraction (CH_2Cl_2), drying (Na_2SO_4) and evaporation of the solvent, pure **3a** was obtained (3.40 g, 98%) as colorless amorphous solid. IR ($CHCl_3$: 1656. ^{1}H NMR (500 MHz, $CDCl_3$): 1.70 (*s*, 6H); 7.41–7.45 *m*, 2H); 7.56–7.61 (*m*, 1H); 7.86–7.90 (*m*, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): 25.9 (*q*); 55.9 (*s*); 104.6 (*s*); 114.2 (*s*); 131.9 (*d*); 132.2 (*d*); 133.4 (*d*); 163.5 (*s*).

4.3. Cyclopropanation of styrene 5a in function of the styrene/ylide ratio

To a suspension of the ylide **3a** (694 mg, 1.0 equiv.) and styrene (0.5–10 equiv.) in CH_2Cl_2 (7.5 mL) was added dodecane (10 μl) as internal standard at room temperature. $[Rh_2(OAc)_4]$ (44 mg, 5%) was added, and the mixture was stirred until complete dissolution of the ylide. The solution was filtered through a plug of silica gel, and the yield of **3a** and **4** was determined by GC using appropriate response factors (Carlo Erba Mega 2 chromatograph with DB-wax column (30 m, 0.32 mm ID), 35°C 2 min; 40°C/min to 50°C, 6°C/min to 180°C, 10°C/min to 240°C (10 min).

4.4. Rh(II)-catalyzed olefin cyclopropanation with 3a; general procedure

The ylide **3a** (1.00 mmol) was suspended in CH_2Cl_2 (8.0 mL). Freshly distilled olefin **5** (10.0 equiv.) and catalyst (5.0 mol%) were successively added under Ar at rt. After 3 h of stirring, the excess of olefin was removed by evaporation, and the residue was purified by flash chromatography (SiO_2, previously treated with Et_3N) or recrystallization to afford the cyclopropanes **6**. With the exception of **6a** and **6e** the cyclopropanes were colorless oils.

4.4.1. 6,6-Dimethyl-1-phenyl-5,7-dioxaspiro[2.5]octane-4,8-dione 6a. Mp 132.5°C. (Lit.[27] 134–136°C. Lit.[17] 133–134°C). IR ($CHCl_3$): 1760, 1738. ^{1}H NMR (500 MHz, $CDCl_3$): 1.73 (*s*, 3H); 1.74 (*s*, 3H); 2.56 (*dd*, $J=9.6$, 4.7, 1H); 2.70 (*dd*, $J=9.5$, 4.7, 1H); 3.46 (*t*, $J=9.5$, 1H); 7.35 (*s*, 5H). ^{13}C NMR (125 MHz, $CDCl_3$): 21.9 (*t*); 26.7 (*q*); 26.9 (*q*); 32.1 (*s*); 43.6 (*d*); 103.9 (*s*); 127.4 (*d*); 127.7 (*d*); 128.4 (*d*); 130.1 (*s*); 162.5 (*s*); 166.7 (*s*). MS: 246 (M^+, 5), 189 (24), 188 (100), 160 (46), 116 (39), 115 (94), 107 (50). HR MS: 246.0929 ($C_{14}H_{14}O_4^+$; calcd 246.0892). Enantiomer separation by HPLC (OD-H column, 25×0.46 cm, isopropanol/hexane 1:9; 0.5 ml/min. $\tau_1=16.9$, $\tau_2=22.4$ min).

4.4.2. 6,6-Dimethyl-1-propyl-5,7-dioxaspiro[2.5]octane-4,8-dione 6b. IR (CH_2Cl_2): 1739. ^{1}H NMR (400 MHz, $CDCl_3$): 0.96 (*t*, $J=7.3$, 3H); 1.41–1.51 (*m*, 2H); 1.58–1.74 (*m*, 2H); 1.77 (*s*, 3H); 1.80 (*s*, 3H); 1.91–1.94 (*m*, 1H); 2.19–2.29 (*m*, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): 13.6 (*q*); 22.0 (*t*); 27.3 (*t*); 27.4 (*q*); 27.6 (*q*); 28.7 (*t*); 29.1 (*s*); 40.9 (*d*); 104.7 (*s*); 165.9 (*s*); 168.5 (*q*). MS: 197 (M^+−15, 10), 155 (28), 154 (35), 137 (42), 136 (100),

125 (43), 111 (50), 108 (49), 99 (78). HR MS: 197.0818 ($C_{10}H_{13}O_4^{+\bullet}$, calcd 197.0814). Enantiomer separation by GC (β-Dex column, 30 m, 0.25 mm ID, 80°C-12 min, 1°C/min to 180°C).

4.4.3. 1-*t*-Butyl-6,6-dimethyl-5,7-dioxaspiro[2.5]octane-4,8-dione 6c. ^{1}H NMR (500 MHz, $CDCl_3$): 1.13 (*s*, 9H); 1.78 (*s*, 3H); 1.88 (*s*, 3H); 2.18–2.23 (*m*, 1H); 2.26–2.40 (*m*, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): 26.9 (*t*); 27.9 (*q*); 28.0 (*q*); 29.7 (*s*); 29.9 (*q*); 32.2 (*s*); 53.4 (*d*); 104.6 (*s*); 165.9 (*s*); 169.2 (*s*). No other data could be obtained owing to decomposition of the product.

4.4.4. 6,6-Dimethyl-1-*cis*-propenyl-5,7-dioxaspiro[2.5]-octane-4,8-dione 6d. IR ($CHCl_3$): 1772, 1734, 1600. ^{1}H NMR (500 MHz, $CDCl_3$): 1.73 (*s*, 3H); 1.77 (*dd*, J= 6.9, 1.9, 3H); 1.78 (*s*, 3H); 2.21 (*dd*, J=8.5, 4.4, 1H); 2.40 (*dd*, J=9.3, 4.4, 1H); 3.00–3.06 (*m*, 1H); 5.38 (*ddq*, J=10.9, 10.6, 1.9, 1H); 5.85 (*dq*, J=10.9, 6.9, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): 13.5 (*q*); 25.1 (*t*); 27.2 (*q*); 27.6 (*q*); 31.9 (*s*); 38.4 (*d*); 105.0 (*s*); 123.3 (*d*); 131.8 (*d*); 165.3 (*s*); 167.9 (*s*). MS: 210 (M^+, 7), 153 (36), 152 (100), 135 (35), 134 (22), 124 (63), 82 (34), 80 (28), 79 (88), 71 (53). HR MS: 210.0875 ($C_{11}H_{14}O_4^+$; calcd 210.0892).

4.4.5. 1-Acetoxy-6,6-dimethyl-5,7-dioxaspiro[2.5]octane-4,8-dione 6e. Crude yield 80%. Partial decomposition upon chromatography to give 40% of colorless crystals, mp 124°C. IR ($CHCl_3$): 1759, 1742. ^{1}H NMR (500 MHz, $CDCl_3$): 1.74 (*s*, 3H); 1.84 (*s*, 3H); 2.08 (*s*, 3H); 2.32 (*dd*, J=7.0, 6.0, 1H); 2.45 (*dd*, J=6.3, 6.0, 1H); 4.76 (*dd*, J=7.0, 6.3, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): 20.2 (*q*); 24.3 (*t*); 27.2 (*q*); 27.7 (*q*); 40.3 (*s*); 63.2 (*d*); 105.9 (*s*); 162.8 (*s*); 166.1 (*s*); 170.5 (*s*). Anal. calcd for $C_{10}H_{12}O_6$: C, 52.63; H, 5.30; found: C, 52.74; H, 5.34.

4.4.6. 2′,2′-Dimethylspiro{bicyclo[4.1.0]heptane-7,5′-[1,3-dioxane]-4′,6′-dione 6f.[28] IR ($CHCl_3$): 1730. ^{1}H NMR (500 MHz, $CDCl_3$): 1.31–1.38 (*m*, 2H); 1.77 (*s*, 6H); 1.67–1.80 (*m*, 4H); 2.00–2.08 (*m*, 2H); 2.61–2.66 (*m*, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): 18.1 (*d*); 20.3 (*q*); 27.4 (*t*); 32.7 (*s*); 35.9 (*t*); 104.0 (*s*); 164.8 (*s*); 169.2 (*s*). MS: 209 (M^+–15, 2), 167 (24), 166 (100), 148 (53), 138 (94), 122 (32), 129 (66), 94 (40), 93 (49), 81 (69), 80 (51), 79 (85), 77 (39).

4.4.7. *cis*-1-Ethyl-2,6,6-trimethyl-5,7-dioxaspire[2.5]-octane-4,8-dione 6i. IR ($CHCl_3$): 1733. ^{1}H NMR (500 MHz, $CDCl_3$): 0.93 (*t*, J=7.3, 3H); 1.31 (*d*, J=6.4, 3H); 1.68 (*s*, 3H); 1.69 (*s*, 3H); 1.74–1.80 (*m*, 2H); 2.43 (*dt*, J=9.5, 7.3, 1H); 2.52 (*dq*, J=9.5, 6.4, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): 6.7 (*q*); 12.1 (*q*); 14.7 (*t*); 26.5 (*q*); 26.6 (*q*); 30.3 (*s*); 37.0 (*d*); 43.2 (*d*); 103.2 (*s*); 163.7 (*s*); 168.4 (*s*). MS: 197 (M^+–15, 6), 155 (22), 154 (28), 139 (24), 136 (100), 113 (27), 108 (22), 82 (309). HR MS: 197.0848 ($C_{10}H_{13}O_4^+$; calcd 197.0814).

4.4.8. *trans*-1-Ethyl-2,6,6-trimethyl-5,7-dioxaspiro[2.5]-octane-4,8-dione 6j. IR (CH_2Cl_2): 1733. ^{1}H NMR (500 MHz, $CDCl_3$): 0.92 (*t*, J=7.4, 3H); 1.37 (*d*, J=6.3, 3H); 1.69 (*s*, 3H); 1.70 (*s*, 3H); 1.74–1.84 (*m*, 2H); 2.28 (*dt*, J=9.4, 7.1, 1H); 2.34 (*dq*, J=9.4, 6.0). ^{13}C NMR (125 MHz, $CDCl_3$): 12.5 (*q*); 13.3 (*q*); 20.2 (*t*); 27.5 (*q*); 27.6 (*q*); 33.4 (*s*). 41.3 (*d*); 48.2 (*d*); 104.3 (*s*); 166.8 (*s*); 167.0 (*s*). MS: 197 (M^+–15), 155 (27), 154 (38), 136 (100); 126 (35), 125 (55), 113 (44), 108 (29), 69 (56), 68 (84); 67 (52). HR MS: 197.0810 ($C_{10}H_{13}O_4^+$; calcd 197.0814).

4.4.9. *trans*-1,6,6-Trimethyl-2-phenyl-5,7-dioxaspiro[2.5]-octane-4,8-dione 6k. ($CHCl_3$): 1731, 1306. ^{1}H NMR (400 MHz, $CDCl_3$): 1.65 (*d*, J=6.3, 3H); 1.72 (*s*, 3H); 1.74 (*s*, 3H); 3.14 (*dq*, J=9.9, 6.3, 1H); 3.59 (*d*, J=9.9, 1H); 7.29–7.36 (*m*, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): 12.2 (*q*); 27.6 (*q*); 27.9 (*q*); 36.1 (*d*); 36.6 (*s*); 49.9 (*d*); 104.4 (*s*); 128.2 (*d*); 128.3 (*d*); 129.3 (*d*); 132.5 (*s*); 164.6 (*s*); 166.3 (*s*). MS: 260 (M^+, 3), 203 (20), 202 (88), 174 (35), 129 (23), 107 (43), 105 (100), 77 (51). HR MS: 260.1054 ($C_{15}H_{16}O_4^+$; calcd 260.1049).

4.4.10. 2-Ethyl-1,1,6,6-tetramethyl-5,7-dioxaspiro[2.5]-octane-4,8-dione 6l. IR ($CHCl_3$): 1767, 1717. ^{1}H NMR (500 MHz, $CDCl_3$): 0.98 (*t*, J=7.4, 3H); 1.36 (*s*, 3H); 1.40 (*s*, 3H); 1.69 (*s*, 3H); 1.73 (*s*, 3H); 1.91–1.98 (*m*, 2H); 2.49 (*t*, J=7.4, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): 13.4 (*q*); 15.9 (*q*); 17.0 (*t*); 21.9 (*q*); 26.6 (*q*); 27.7 (*q*); 37.5 (*s*); 44.8 (*d*); 45.3 (*s*); 103.4 (*s*); 165.2 (*s*); 166.6 (*s*). MS: 211 (M^+–15, <1); 169 (8); 168 (88), 151 (17); 150 (55), 139 (16), 83 (20), 82 (100), 81 (22).

4.5. Abs. configuration of 6,6-dimethyl-1-phenyl-5,7-dioxaspiro[2.5]octane-4,8-dione 6a

4.5.1. (*E*)- and (*Z*)-Methyl 1-carboxy-2-phenylcyclopropane-1-carboxylate 7a. To the cyclopropane **6a** resulting from cyclopropanation of styrene with [Rh_2{(*S*)-nttl}$_4$], (210 mg, 0.86 mmol) $[\alpha]_D^{22}$ +68.6 (*c* 0.87, $CHCl_3$, for 36% ee) in MeOH (10 mL) was added NaOMe in MeOH (1.86 M, 500 μl, 0.86 mmol). After 3 h of stirring at rt the solvent was evaporated and the residue was dissolved in 5% citric acid (15 mL). The aqueous layer was extracted (EtOAc), and the organic phase was washed with satd NaCl (15 mL). After drying (Na_2SO_4) the solvent was evaporated, and the residue was purified by flash chromatography (SiO_2, CH_2Cl_2+2% MeOH) to afford a *cis*/*trans* mixture of monoesters **7a** (108 mg, 62%) with 60% de. ^{1}H NMR (400 MHz, $CDCl_3$): 2.20 (*dd*, J=9.5, 4.8, 1H); 2.50 (*dd*, J=8.8, 4.8, 1H); 3.34 (*t*, J=9.2, 1H); 3.89 (*s*, 3H); 7.26–7.31 (*m*, 5H).

4.5.2. (*R*)-Dimethyl 2-phenylcyclopropane-1,1-dicarboxylate 8a. To the monoester **7a** (108 mg, 0.49 mmol) in benzene/MeOH 4:1 (5 mL) was added $TMSCHN_2$ (2 M in hexane, 345 μl, 0.69 mmol) dropwise. The mixture was stirred 1.5 h at rt, and the solvent was evaporated. The residue was purified by flash chromatography (SiO_2, AcOEt/pentane 15:85) to afford **8a** (83.3 mg, 72%). $[\alpha]_D^{22}$ +44.5 (*c* 1.1, PhH for 26% ee (by GC, β-dex. 150°C, τ_1=75.2, τ_2=75.95 min)). Lit: $[\alpha]_D^{23}$ −137.2 (*c* 1.1, PhH, for (*S*)-**8a** having 92% ee).[18] ^{1}H NMR (500 MHz, $CDCl_3$): 1.76 (*dd* J=5.1, 9.2, 1H); 2.21 (*dd* J=5.4, 8.2, 1H); 3.24 (*t*, J=8.9, 1H); 3.37 (*s*, 3H); 3.80 (*s*, 3H); 7.18–7.22 (*m*, 5H).

4.6. Abs. configuration of 6,6-dimethyl-1-propyl 5,7-dioxaspiro-[2.5]octane-4,8-dione 6b

4.6.1. (*E*)- or (*Z*)-Methyl 1-carboxy-2-propylcyclopropane-1-carboxylate 7b. The cyclopropane **6b** resulting from cyclopropanation of pent-1-ene with $[Rh_2\{(S)\text{-nttl}\}_4]$ (1.38 g, 6.40 mmol, 59% ee) was dissolved in abs. MeOH. KOH (443 mg, 6.4 mmol) was dissolved in abs. MeOH (10 mL), and was added dropwise to the reaction mixture. After 2 h of stirring at room temperature, the solvent was evaporated, and the resulting salt was dissolved in aq. citric acid (5%). The aqueous layer was extracted with AcOEt (4×20 mL), the organic phase was dried (Na_2SO_4) and filtered. Evaporation of the solvent afforded a colorless oil (1.08 g, 89%) of 60% de (by NMR), $[\alpha]_D^{20}$ −15.6 (*c* 1.26, $CHCl_3$). IR: 2959, 1727*s*, 1698*s*, 1430. ^{1}H NMR (500 MHz, $CDCl_3$): 0.91 (*t*, *J*=7.4, 3H); 1.33–1.46 (*m*, 2H); 1.63–1.69 (*m*, 2H); 1.86 (*dd*, *J*=4.1, 8.7, 3H); 1.96 (*dd*, *J*=4.1, 9.3, 1H); 1.99–2.08 (*m*, 1H); 3.75 (*s*, 3H). ^{13}C NMR (125 MHz): 13.6 (*q*); 22.2 (*t*); 24.3 (*t*); 28.6 (*t*); 30.7 (*s*); 37.6 (*d*); 53.4 (*q*); 168.6 (*s*); 176.2 (*s*). MS: 187 (M^++1, 3), 139 (10), 137 (16), 131 (30), 125 (18), 118 (14), 113 (14), 113 (100), 111 (14), 109 (10), 108 (44), 99 (59), 97 (13), 83 (13), 81 (38), 80 (30), 79 (21), 69 (27), 68 (57), 67 (23), 59 (44), 56 (28), 54 (20), 53 (72), 52 (13), 51 (17). HR MS: 187.0999 ($C_9H_{15}O^+$; calcd 187.0970).

4.6.2. (*R*)-Dimethyl 2-propylcyclopropane-1,1-dicarboxylate 8b. To the monoester **7b** (541 mg, 2.87 mmol) in abs. MeOH (5.0 mL) and benzene (20 mL) was added dropwise trimethylsilyldiazomethane (2 M in hexane, 2.0 mL, 4.0 mmol). After 40 min a few drops of AcOH were added, and the solvent was evaporated. The resulting residue was purified by bulb-distillation (4 Torr, 100°C) to afford (*R*)-**8b** (552 mg, 96%) having 58% ee (by GC, β-Dex column, 80°C (20 min), 1°C/min to 180°C (10 min), τ_1=42.5 min; τ=42.9 min. $[\alpha]_D^{20}$ +27.4 (*c* 1.10, $CHCl_3$) for 58% ee. IR (neat): 2957, 1724*s*, 1209*s*, 1128*s*. ^{1}H NMR (400 MHz, $CDCl_3$): 0.92 (*t*, *J*=7.1, 3H); 1.08–1.19 (*m*, 1H); 1.36–1.51 (*m*, 5H); 1.87–1.94 (*m*, 1H); 3.72 (*s*, 3H); 3.75 (*s*, 3H). ^{13}C NMR. (100 MHz): 13.7 (*q*); 21.4 (*t*); 22.0 (*t*); 28.6 (*d*); 30,7 (*t*); 33.8 (*s*); 52.4 (*q*); 52.6 (*q*); 168.8 (*s*); 171.0 (*s*). MS: 169 (M^+–MeO, 9), 145 (27), 138 (12), 137 (14), 136 (34), 132 (42), 113 (100), 108 (25), 81 (15), 69 (11), 68 (21), 59 (30), 53 (11). HR MS: 169.0860 ($C_9H_{13}O_3^+$; calcd 169.0865).

4.7. Synthesis of $[Rh_2\{(S)\text{-nttl}\}_4]$

4.7.1. (*S*)-*N*-1,8-Naphthoyl-*t*-leucine 10. A mixture of L-*t*-leucine (1.01 g, 7.72 mmol) and 1,8-naphthalic anhydride (**9**, 1.71 g, 8.60 mmol) in DMF (25 mL) was heated to reflux for 1.0 h under N_2. The solvent was evaporated and the light-brown residue was purified by chromatography (SiO_2, Et_2O/MeOH 99:1) to afford **10** (2.28 g, 93%) as brownish solid. Mp 174–175°C (EtOH). $[\alpha]_D^{24}$ −83 (*c* 0.47, $CHCl_3$). IR (KBr): 3199*br*, 2956*m*, 2936*m*, 1753*s*, 1702*s*, 1656*s*, 1588*s*, 1383*s*, 1341*s*, 1243*s*, 1182*s*, 1182*m*, 1151*m*, 1113*w*, 980*w*, 908*m*, 848*m*, 780*s*, 742*w*, 670*m*. ^{1}H NMR (500 MHz, DMSO-d_6): 1.16 (*s*, 9H); 5.39 (*s*, 1H); 7.92–7.96 (*m*, 2H); 8.55 (*d*, *J*=7.9, 3H); 8.61 (*d*, *J*=7.3, 1H). ^{13}C NMR (125 MHz, DMSO-d_6): 18.9 (*q*); 35.7 (*s*); 59.5 (*d*); 121.7 (*s*); 122.1 (*s*); 127.6 (*s*); 127.8 (*d*); 131.5 (*d*); 131.6 (*d*); 132.1 (*d*); 135.1 (*d*); 135.2 (*d*); 163.6 (*s*); 164.4 (*s*); 169.7 (*s*). MS: 311 (M^+, abs.), 255 (49), 237 (100), 182 (35), 154 (38). HR MS: 311.1188 ($C_{18}H_{17}O_4N^+$; calcd 311.1158).

4.7.2. Synthesis of $[Rh_2\{(S)\text{-nttl}\}_4]$. $[Rh_2(OAc)_4]$ (110 mg, 0.25 mol) and (*S*)-*N*-*t*-leucine (773 mg, 2.40 mmol) were heated to reflux under N_2 in chlorobenzene in a flask fitted with a soxhlet extractor containing a mixture of anhydrous Na_2CO_3 and sand. After 24 h the solvent was evaporated and the gummy residue was purified by flash chromatography (Alox basic, Et_2O) to afford $[Rh_2\{(S)\text{-nttl}\}_4]$ which was precipitated from acetonitrile to afford pure catalyst (835.0 mg, 92%). $[\alpha]_D^{24}$ +71 (*c* 0.10, $CHCl_3$. IR (KBr): 3463*br*, 3968*w*, 2955*s*, 2870*w*, 1708*s*, 1665*s*, 1589*s*, 1514*w*, 1482*m*, 1434*m*, 1398*s*, 1302*m*, 1238*s*, 1181*s*, 1150*w*, 1111*w*, 1074*w*, 1028*w*, 995*w*. ^{1}H NMR (500 MHz, $CDCl_3$): 1.30 (*s*, 9H); 5.84 (*s*, 1H); 7.32 (*t*, *J*=7.6, 1H); 7.73 (*t*, *J*=7.9, 1H); 7.83 (*d*, *J*=7.9, 1H); 7.92 (*d*, *J*=8.1, 1H); 8.24 (*d*, *J*=6.9, 1H); 8.71 (*d*, *J*=7.2, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): 28.8 (*q*); 36.6 (*s*); 61.8 (*d*); 122.4 (*s*); 122.7 (*s*); 126.3 (*d*); 127.3 (*d*); 127.6 (*d*); 130.7 (*d*); 130,9 (*s*); 132.0 (*d*); 133.2 (*d*); 133.4 (*d*); 163.0 (*s*); 164.7 (*s*); 187.3 (*s*). MS(ES, CH_2Cl_2/MeOH 5:1): 1469.5 (M^++23, 100). Anal. calcd for $C_{18}H_{17}NO_4Rh_2$: C, 59.76; H, 4.46; N, 3.87; found: C, 59.64; H, 5.00; N, 3.53.

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