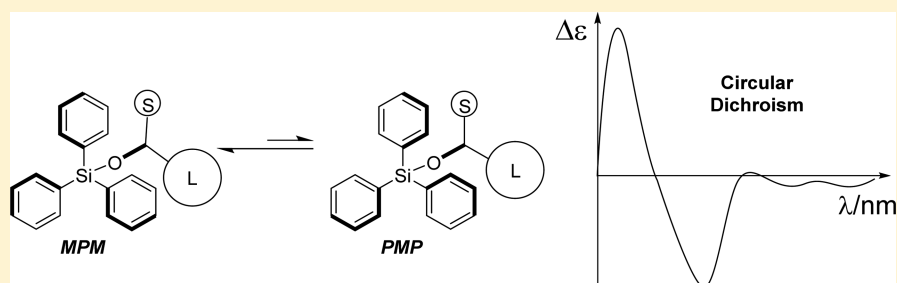


Understanding Internal Chirality Induction of Triarylsilyl Ethers Formed from Enantiopure Alcohols

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S Supporting Information



ABSTRACT: Chirality transmission from point chirality to helical chirality was explored using triarylsilyl ethers. Circular dichroism (CD) spectroscopy was employed to show that the alcohol stereocenter of silylated, enantiopure secondary alcohols can transmit chirality to the aryl groups on the silicon resulting in a higher population of one helical conformation over another. Cotton effects characteristic of the aryl groups organized into one preferred conformation were observed for all of the compounds examined, which included both triphenyl- and trinaphthylsilyl groups. Alcohols with an *R* configuration typically induced a *PMP* helical twist, while an *S* configuration induced a *MPM* helical twist. Molecular modeling combined with solid-state structures also gave evidence signifying that point chirality adjacent to triphenylsilyl groups could bias the conformation of the phenyl groups. This work helps in our understanding of the origin of selectivity in our silylation-based kinetic resolutions and a role the phenyl groups play in that selectivity.

INTRODUCTION

The induction of chirality, either intra- or intermolecularly, is a topic of current interest and is important in areas ranging from asymmetric catalysis^{1–3} to sensing.^{4,5} Molecular propellers are an interesting class of molecules that have been studied over the years where a particular gearing in the propeller can be induced by transmission or communication of chiral information from a source of point chirality.^{6–12} Specifically, we are interested in propellers or helical twists that are formed from three aryl groups around a central atom and ways to induce one propeller/helical twist form over another. We wanted to know whether a molecule with point chirality could induce helical chirality (*M* or *P*) in a triphenylsilyl group if the two were covalently linked (Figure 1). Gearing of the phenyl groups has been accomplished with a trityl group,^{7,8,13} but there is a difference in size and bond lengths between silicon and

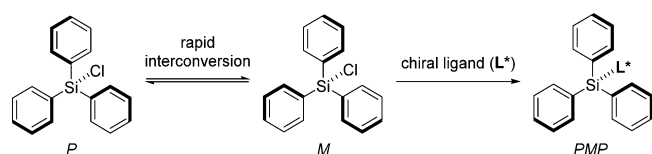


Figure 1. Helical formation of triphenyl groups induced by a chiral ligand.

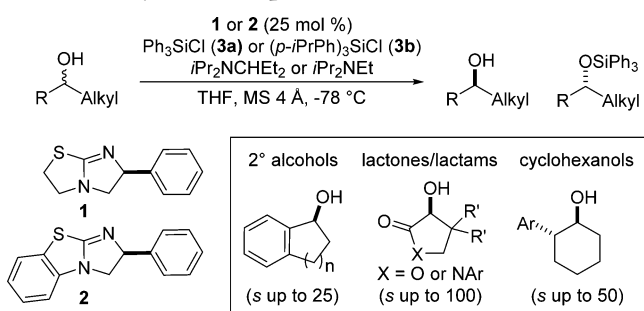
carbon. Herein we explore this induction of chirality in enantiopure alcohols protected as triarylsilyl ethers. The circular dichroism (CD) spectrum shows a characteristic Cotton effect indicating a helical twist formation, and the helicity of the propeller is explored through crystal structures and molecular modeling.

Our interest in the induction of chirality in a triphenylsilyl group stems from the silylation-based kinetic resolution methodology developed within our group (Scheme 1).^{14–16} A kinetic resolution^{17–21} is a powerful method of separating enantiomers by performing a reaction on one enantiomer and leaving the other enantiomer unreacted. Our methodology selectively silylates one alcohol enantiomer, resulting in the enantiomeric enrichment of the unreacted alcohol enantiomer. The reaction employs a chiral isothioureia catalyst (1 or 2)²² and triphenylsilyl chloride (3a) or derivatives thereof (3b), where the phenyl groups on the silyl chloride have shown to be important for selectivity. We theorize that the phenyl groups aid in chirality transmission when the nucleophilic catalyst reacts with the silyl chloride to form a reactive intermediate and a helical twist in the triphenylsilyl group is induced by the chiral catalyst attached to the silicon. This helical formation of

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Scheme 1. Previous Silylation-Based Kinetic Resolutions Performed by Our Group



triphenyl groups would enhance the chiral space around the catalyst aiding in selectivity. Because the catalyst complex is highly reactive and thus far undetectable, we moved to an analogue that can be easily handled and characterized to see if attaching a compound with point chirality would induce chirality in the triphenylsilyl group.

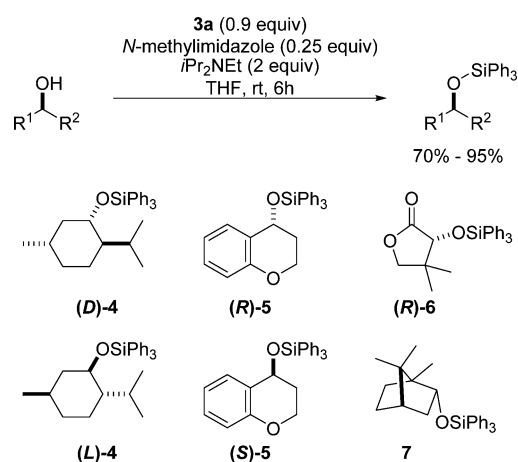
Mislow and co-workers began work on propeller systems stemming from three aryl groups around a tetrahedral core atom 40 years ago.^{23–26} The aryl groups in these types of systems have restricted rotation and display conformational isomerism as two enantiomers, *M* and *P* (Figure 1). To form the lowest energy species, the aryl groups all have the same sense of twist when the molecule has true C_3 symmetry ($X = \text{Cl}, \text{H}, \text{etc.}$). More recently, Gawroński and co-workers synthesized trityl ethers of chiral secondary alcohols, which act as molecular bevel gears to transmit chirality from the alcohol to the trityl group.⁷ The addition of enantiopure point chirality results in the gearing of the trityl phenyl groups into predominately one conformational isomer. With the lack of true C_3 symmetry ($X = \text{OR}$), they discovered one of the aryl groups has a different twist than the other two, but the trityl group still had stereoisomerism (either in a *PMP* or *MPM* helicity). This could be detected via circular dichroism, showing strong Cotton effect patterns from the helicity of the trityl groups. While the triphenylsilyl group is found throughout the literature due to its use as a protecting group,²⁷ to our knowledge induction of point chirality to the triarylsilane has not been studied. Because silicon containing bonds are longer compared to carbon (i.e., C–Si bond $\sim 1.9 \text{ \AA}$ versus C–C bond $\sim 1.5 \text{ \AA}$) and silicon has a larger van der Waals radius than carbon,²⁸ there was a question of whether the components of a triarylsilyl group were too far apart for the induction of one helical structure over another via point chirality. Therefore, the investigation of this phenomenon was needed to gain a better understanding of the selectivity of our silylation methodology.

RESULTS AND DISCUSSION

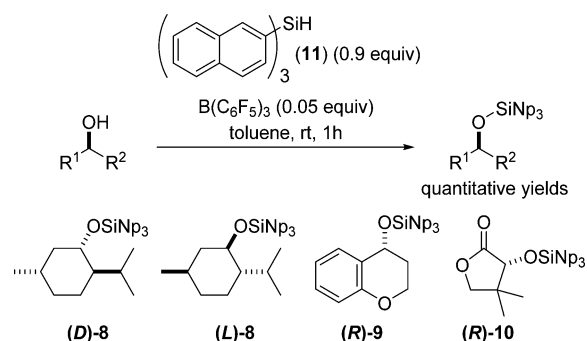
Circular dichroism (CD) spectroscopy is a powerful tool for investigating the three-dimensional space of compounds.^{29–31} It is most commonly employed to study the structure of proteins,^{32–34} but has also been employed to study the configuration of smaller organic compounds.^{35,36} CD spectroscopy relies on the principle that nonracemic chiral molecules absorb left and right circularly polarized light differently. Thus, we wanted to explore the conformational properties of a triarylsilyl group covalently bonded to enantiopure alcohols by this method. If the alcohol transmits chirality to the aryl groups, a characteristic Cotton effect should be present in the 180–210 nm range of the spectrum indicating the three aryl groups

formed a higher percentage of one helical twist.⁷ The lack of a new signal in that region suggests that there is no preference for one twist over the other, because equal ratios of two opposite helical twists would not be CD active. Ultimately, the preference for one helical twist and the presence of point chirality means the molecule is a conformational diastereomer. A series of enantiopure secondary alcohols (*D/L*-menthol, (*R/S*) chromanol, (*R*)-pantolactone, and (–)-borneol) were silylated with triphenyl- and trinaphthylsilyl groups to test this phenomenon. Trinaphthylsilyl groups were incorporated in the study in an attempt to shift the Cotton effect originating from the preferred gearing of the aryl groups to longer wavelengths versus triphenylsilyl groups. The triphenylsilyl ether compounds 4–7 were synthesized by protecting the alcohols with triphenylsilyl chloride catalyzed by *N*-methylimidazole (Scheme 2). The 2-substituted trinaphthylsilyl ethers (8–10) were obtained by a tris(pentafluorophenyl)borane catalyzed silylation³⁷ using trinaphthylsilane (11) (Scheme 3).

Scheme 2. Synthesis of Enantiopure Triphenylsilyl Ethers



Scheme 3. Synthesis of Enantiopure Trinaphthylsilyl Ethers



Circular Dichroism Analysis. Silyl ethers 4–10 were investigated by CD spectroscopy, and a Cotton effect, characteristic for the helical twist of triaryl groups, was observed for all the compounds. The compounds were dissolved in solutions of pentane in cyclohexane (1–10% v/v) or 2-propanol in cyclohexane (3.5% v/v) at a concentration of approximately 80 μM . These solvents were chosen to avoid a background absorbance of the solvent in the same region of the spectra where the phenyl groups on the silicon absorb.

Triphenylsilyl ethers (*L*)-4 and 7 (Table 1, entries 1 and 3) were employed to provide a direct comparison to the CD spectra of the trityl ether versions of these compounds from the

Table 1. Selected CD Data ($\Delta\epsilon$ (nm)) for Chiral Triphenylsilyl Ethers

entry ^a	triphenyl silyl ether	CD $\Delta\epsilon$ (nm)	CD $\Delta\epsilon$ (nm)	predicted helicity
1	(L)-4	6.7 (205)	-13.4 (192)	<i>MPM</i>
2	(D)-4	-7.5 (204)	14 (190)	<i>MPM</i>
3	7	-17 (196)	29 (186)	<i>MPM</i>
4 ^b	(R)-5	23 (202)	-10 (190)	<i>MPM</i>
5 ^b	(S)-5	-23 (202)	15 (191)	<i>MPM</i>
6 ^c	(R)-6	1.9 (210)	-7.2 (199)	<i>MPM</i>

^aData was collected at 80 μ M (1% pentane in cyclohexane (v/v)) with a 0.1 cm path length quartz cell. ^b10% pentane in cyclohexane (v/v). ^c3.5% 2-propanol in cyclohexane (v/v).

literature. These silyl ethers display the same Cotton effects as the trityl versions of these compounds,⁷ indicating that an induction of chirality is indeed taking place from the enantiopure alcohols to the triphenylsilyl groups, presumably resulting in the same helical twist as the trityl compounds. Compound (L)-4 has a positive Cotton effect,³⁸ which can tentatively be assigned as the *PMP* helical twist based on the model developed by Gawroński (Figure 2a).⁷ The model

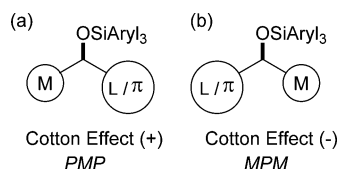


Figure 2. Model of the correlation between the position of the large substituent⁷ (L) or π system to the resultant Cotton effect and helical twist.

depends on the size of the substituents around the stereocenter, not the absolute configuration, which was correlated to the Cotton effect obtained and the helical twist expected. Its enantiomer (D)-4 (Table 1, entry 2) as well as 7 display an opposite Cotton effect (negative), suggesting an *MPM* helical twist (Figure 2b).⁷ The results from (L)-4 and (D)-4 indicate that the opposite point chirality induces the opposite helical twist.

Silyl ethers 5 and 6 were a little more complicated. The alcohols used to synthesize 5 and 6 are also CD active at low wavelengths, causing an overlap of signals.³⁸ To more clearly discern the Cotton effect resulting from the helical twist of the triphenylsilyl group, the CD spectrum of the free alcohols was subtracted from the CD spectrum of the silyl ether compounds. These results are given in Table 1, entries 4–6. A positive Cotton effect is obtained for compounds (R)-5 and (R)-6, indicating a *PMP* helicity (entries 4 and 6). The π system adjacent to the stereocenter now plays a more dominant role in directing the helical twist of the triphenylsilyl group (Figure 2a). The *S* enantiomer of 5 again generates the opposite result, with a predicted *MPM* helicity for the negative Cotton effect (entry 5). These results show that even with the longer silicon bond lengths, one helical twist is predominately formed over another due to the point chirality of the alcohols.

By extending the conjugation of the aromatic rings on silicon via changing the phenyls to naphthyls, the CD spectra associated with the helical twist is shifted to longer wavelengths, therefore eliminating solvent interference and improving accuracy. Trinaphthylsilyl ethers 8–10 were employed as direct

comparisons to the triphenylsilyl ethers 4–6. The trinaphthylsilyl ethers all exhibited red shifts in the CD spectra of 20–30 nm (Table 2) as would be expected with a change from

Table 2. Selected CD Data ($\Delta\epsilon$ (nm)) for Chiral Trinaphthylsilyl Ethers

entry ^a	trinaphthyl silyl ether	CD $\Delta\epsilon$ (nm)	CD $\Delta\epsilon$ (nm)	predicted helicity
1	(L)-8	4.9 (236)	-5.3 (220)	<i>MPM</i>
2	(D)-8	-4.6 (236)	4.8 (220)	<i>MPM</i>
3 ^b	(R)-9	27 (229)	-23 (213)	<i>MPM</i>
4 ^c	10	5.3 (232)	-4.1 (214)	<i>MPM</i>

^aData was collected at 80 μ M (1% pentane in cyclohexane (v/v)) with a 0.1 cm path length quartz cell. ^b10% pentane in cyclohexane (v/v). ^c3.5% 2-propanol in cyclohexane (v/v).

phenyl to naphthyl groups.³⁹ All the compounds exhibited the same Cotton effects as their phenyl counterparts (i.e., (L)-8 (Table 2, entry 1) has the same positive Cotton effect as (L)-4 (Table 1, entry 1)), and the pair of enantiomers still displayed opposite Cotton effects ((L)-8 and (D)-8, Table 2, entries 1 and 2). Again, the CD spectra for silyl ethers 9 and 10 overlapped with the spectra of the basic core structure of the alcohol. Therefore, the CD spectra of the free alcohols were subtracted from the CD spectra of the trinaphthylsilyl ether compounds to get the data in entries 3 and 4, Table 2. All of these results show that point chirality can still induce a helical twist in the trinaphthylsilyl group, and the orientation of these aryl groups matches the results from the phenylsilyl ether equivalents.

Crystal Structure Analysis. Crystal structures were obtained of the triphenylsilyl ethers (R)-5, (S)-5, and 7, showing the orientation of the phenyl groups on the silicon in the solid phase. See Supporting Information for additional views. (For other examples of crystal structures of triphenylsilyl compounds see reports in the literature^{40–42}). Both enantiomers of 5 were crystallized independently, and the resulting structures showed the phenyl groups on the silicon oriented in the same but opposite pattern for the two enantiomers (Figure 3). To quantitatively assign each phenyl group as *M* or *P*, a dihedral angle (ω) was measured between the O–Si bond and the closest C_{ipso}–C_{ortho} bond, for each phenyl group. Looking down the C_{ipso}–Si bond, if the turn from the C_{ipso}–C_{ortho} bond to the Si–O bond is clockwise, ω is positive and the phenyl is assigned *M*; if the turn is counterclockwise, ω is negative and the phenyl is assigned *P*.

The measured dihedral angles and resulting phenyl group helicity assignments are shown in Table 3 for (R)-5, (S)-5, and 7. Enantiomers (R)- and (S)-5 have opposite helical twists of the triphenylsilyl groups as one would expect, with very similar angles but different signs. The solid-phase structures matched the predicted conformations from the CD data, resulting in a *PMP* helical twist for (R)-5 and a *MPM* helical twist for (S)-5 (Table 1, entries 4 and 5 vs Table 3, entries 1 and 2). The pattern of one phenyl group being geared opposite the other two comes from the lack of C₃ symmetry discussed previously.⁷ These structures also show that the silicon–oxygen bond lengths (1.64 Å) and silicon–carbon bond lengths (1.86–1.87 Å) in the crystal structures are similar to literature values,²⁸ again signifying that helical twist formations are possible even with these extended bond lengths versus a trityl group.

However, when the bicyclic compound 7 was crystallized, two independent conformational stereoisomers crystallized in

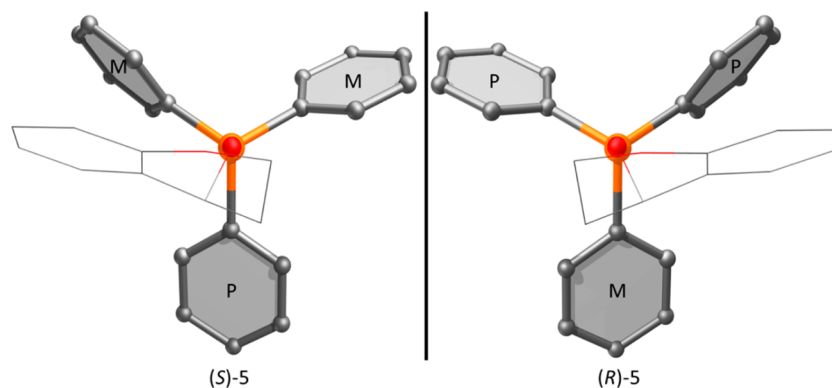


Figure 3. Independent molecular structures of (*S*)- and (*R*)-**5** as viewed down the oxygen–silicon bond. The alcohol portion of the molecule is drawn in wireframe, and the hydrogens are removed for clarity. The crystals of (*S*)-**5** and (*R*)-**5** were grown independently and are enantiomerically pure; all molecules in the crystals are identical. C1 was determined by the X-ray data to have the “*S*” configuration for (*S*)-**5** and the “*R*” configuration for (*R*)-**5**.

Table 3. Dihedral Angles and Helicity Types of (*R*)-**5**, (*S*)-**5**, and **7**

entry	alcohol	ω_1	ω_2	ω_3	helicity type
1	(<i>R</i>)- 5	−34	75	−16	<i>PMP</i>
2	(<i>S</i>)- 5	32	−76	17	<i>MPM</i>
3a	7	−45	−50	−37	<i>PPP</i>
3b	7	31	61	40	<i>MMM</i>

the asymmetric unit cell of the crystal (Figure 4). Even though the CD spectra suggested one helical twist was preferred in

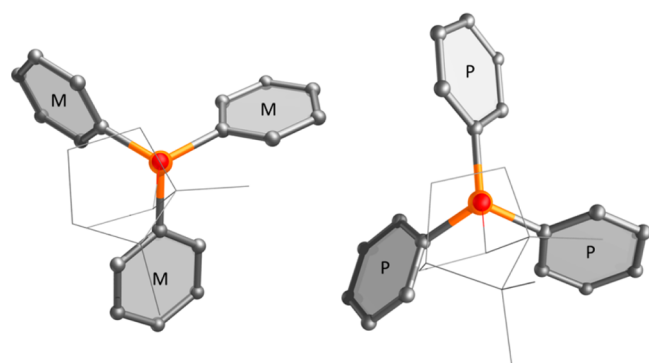


Figure 4. Structure of two independent, chemically identical but conformationally distinct molecules of **7** as viewed down the oxygen–silicon bond. The alcohol portion of the molecule is drawn in wireframe, and the hydrogens are removed for clarity.

solution (Table 1, entry 3), in the solid phase two helical twists formed from the (−)-borneol triphenylsilyl ether. The two conformational diastereomers resulted in helical twists of *MMM* and *PPP* which are true propeller formations. (Table 3, entry 3a,b). The presence of these two stereoisomers does not necessarily suggest that the two conformational diastereomers are present in equal amounts but that two successfully pack well in the solid state. Molecular modeling (below) provided additional support toward our CD findings that there is a preference for one stereoisomer in solution over two solid-state structures.

Molecular Modeling Analysis. To further investigate the structure of the low energy conformations in these triphenylsilyl ethers, molecular modeling using a Monte Carlo search was employed for (*S*)-**5** and **7**. All of the conformers

within 2 kcal/mol of the lowest energy conformation were selected, and geometry optimization was performed using density functional theory (DFT), specifically B3LYP^{43,44} and 6-311++G** basis set.⁴⁵ Three types of triphenylsilyl conformers resulted from the modeling of (*S*)-**5**, with the predominant one having an *MPM* helical twist (92%) and only small percentages of the less thermodynamically stable conformers *MMM* (6%) and *PMP* (2%) (Table 4, entry 1 to 4). This result (*MPM*

Table 4. Population of Helicity Types and Calculated Dihedral Angles of (*S*)-**5** and **7**

entry	silyl ether	conformer distribution (%)	ω_1	ω_2	ω_3	helicity type
<i>MPM:MMM:PMP</i> = 92:6:2						
1	(<i>S</i>)- 5	23	24	−7	87	<i>MPM</i>
2		69	1	−88	15	<i>MPM</i>
3		6	83	28	28	<i>MMM</i>
4		2	−69	9	−18	<i>PMP</i>
<i>MMM:PPP</i> = 85:15						
5	7	85	79	31	32	<i>MMM</i>
6		15	−35	−29	−78	<i>PPP</i>

preference) is consistent with the predicted helicity from the CD experiments (Table 1, entry 5) as well as the conformation in the crystal structure of (*S*)-**5** (Table 3, entry 2).

The CD spectroscopy of **7** indicated a higher population of the conformation with an *MPM* configuration, while the solid-state structure indicated the presence of two stereoisomers (*MMM* and *PPP*). A Monte Carlo search resulted in two low energy triphenylsilyl conformations, the *MMM* and *PPP* stereoisomers (Table 4, entries 5 and 6), consistent with the solid-state structure. After DFT geometry optimization, the structures were shown to have an energy difference of 1.1 kcal/mol with a preference for the *MMM* helical twist, leading to a ratio of 85 to 15 of the *MMM* to *PPP* helicity, respectively. This preference for the *MMM* helical twist would result in a negative Cotton effect curve in the CD spectra, which is consistent with our observed experimental outcome (Table 1, entry 3). The tied-back nature of bicyclic **7** offers less steric hindrance compared to the other substrates studied, resulting in a smaller energy difference between the two conformations, leading to an increased presence of the higher energy conformation. This bicyclic structure ultimately affects the resulting helical twist, allowing for a true propeller formation.

CONCLUSIONS

We successfully showed that point chirality can induce helical chirality in triarylsilyl groups by derivatizing enantiopure alcohols with triphenylsilyl and trinaphthylsilyl groups and exploring the conformations of the triarylsilyl groups through CD spectroscopy, solid-state structures, and molecular modeling. CD spectroscopy of the compounds all displayed a Cotton effect that was characteristic for a helical twist formation, with *R* configuration alcohols generally exhibiting positive Cotton effects indicating a *PMP* helical twist, and *S* configuration alcohols exhibiting negative Cotton effects indicating a *MPM* helical twist. The crystal structures for (*R*)- and (*S*)-**5** each crystallized as one conformation, with the gearing of the phenyl groups consistent with the proposed helicity determined from CD spectroscopy. Molecular modeling of (*S*)-**5** was performed through a Monte Carlo search predicting the same conformation as was determined experimentally. Even though compound **7** crystallized as two conformational diastereomers, molecular modeling resulted in the *MMM* helical twist as the low energy conformation which would give the same negative CD signal that was obtained experimentally. Ultimately, the understanding of chirality transmission between the alcohol and the triarylsilyl group can be extrapolated to explain the importance of phenyl groups in silylation-based kinetic resolutions through potential gearing of the phenyl groups when a chiral, nucleophilic catalyst attacks a triphenylsilyl chloride. This gearing through point chirality transmission could also be exploited as a derivatizing reagent for determining the enantiomeric excess of alcohols through CD spectroscopy. Future studies will be focused on continuing to elucidate the mechanism of asymmetric silylation.

EXPERIMENTAL SECTION

General Information. Trinaphthylsilyl and all the triarylsilyl ethers were obtained through the general procedures below. Reactions were carried out under a nitrogen atmosphere using oven-dried glassware. Tetrahydrofuran (THF), toluene, and diethyl ether were degassed and passed through a column of activated alumina prior to use. Unless otherwise stated, all the other chemicals, including the enantiopure starting alcohols, were obtained from major commercial sources and used without further purification. High resolution mass spectrometry (HRMS) was obtained either using an orthogonal quadrupole time-of-flight instrument or an orbitrap instrument. Infrared spectroscopy (IR) was conducted using an FT-IR ATR spectrophotometer, ν_{\max} in cm^{-1} . NMR spectra were recorded with a 400 MHz instrument for ^1H and a 101 MHz instrument for ^{13}C with complete proton decoupling. Chemical shifts were reported in ppm with TMS or chloroform as an internal standard (TMS 0.00 ppm or CHCl_3 7.26 ppm for ^1H and 77.16 for ^{13}C). Optical rotations were obtained utilizing a polarimeter. Circular dichroism (CD) spectra were taken at concentrations of approximately 8×10^{-5} M, aiming to reach a maximum absorbance without oversaturating the detector.⁴⁶ The samples were analyzed in a 1 mm path length, strain free, quartz cell to have a better observed Cotton effect while minimizing noise. All reported spectra were processed by using 15-point Sactizy-Golay smoothing.⁴⁷ Structure determinations were performed using standard single-crystal X-ray diffraction techniques. See [Supporting Information](#) for full experimental and structure refinement details.

General Procedure for the Preparation of Triphenylsilyl Ether Derivatives (GP1). To a 4-dram vial with a stir bar were added the enantiopure alcohol (1 equiv), *N,N*-diisopropylethylamine (0.9 equiv), and *N*-methylimidazole (0.25 equiv). Dry THF was then added to obtain a concentration of 0.3 M with respect to alcohol. The solution was stirred at room temperature for 5 min followed by the addition of triphenylsilyl chloride in a THF solution (0.6 M, 0.9 equiv). The reaction was allowed to react for 24 h at room

temperature, and the crude reaction was concentrated under vacuum. The residue was then purified via silica gel chromatography (2% EtOAc to 5% EtOAc in hexane).

Preparation of Tri(naphthalen-2-yl)silane (11).⁴⁸ A 250 mL round-bottom flask was fitted with a stir bar and septa and purged with argon. The flask was charged with 20 mL of ether, and the solution was allowed to cool to 0 °C in an ice bath. *N*-Butyllithium (10.25 mmol, 8.1 mL of 1.26 M in hexane) was added via syringe with stirring. A solution of 1-iodonaphthalene (10 mmol, 1.46 mL in 20 mL ether) was prepared and added to the reaction vessel slowly via syringe. The mixture was then allowed to warm to room temperature for 1 h. The mixture was then cooled to -40 °C in a dry ice/MeCN bath. A solution of trichlorosilane Cl_3SiH (3.0 mmol, 303 μL in 7.5 mL of ether) was prepared and added to the reaction slowly via syringe. The reaction was left to stir at -40 °C for 2 h and then quenched with water. A significant quantity of solid formed. The solid was filtered and washed with cold acetone to reveal a white solid, 0.99 g, 80% yield.

^1H NMR (400 MHz, CDCl_3): δ ppm 8.16 (s, 3H), 7.89–7.83 (m, 6H), 7.80 (d, $J = 7.9$ Hz, 3H), 7.71 (d, $J = 8.2$ Hz, 3H), 7.56–7.44 (m, 6H), 5.85 (s, 1H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 137.3, 134.2, 133.1, 131.5, 130.8, 128.3, 127.8, 127.5, 126.9, 126.1

General Procedures for the Preparation of Trinaphthylsilyl Ether Derivatives (GP2). Synthesis of trinaphthylsilyl ether derivatives followed a procedure similar to that reported in the literature.³⁷ To a 4-dram vial that was oven-dried with a stir bar were added enantiopure alcohol (1 equiv) and trinaphthylsilyl ether (0.9 equiv) under N_2 . Commercially available tris(pentafluorophenyl)borane ($\text{B}(\text{C}_6\text{F}_5)_3$) (0.02 equiv) was added to the mixture in a glovebox. Enough toluene was then added to make a concentration of 0.5 M with respect to alcohol. The reaction was then stirred at room temperature and was monitored through ^1H NMR. Full conversion was achieved after 1 h. The crude mixture was concentrated under vacuum, and the residue was purified via silica gel chromatography (2% EtOAc to 5% EtOAc in hexane).

Characterization Triarylsilyl Ether Derivatives. ((1*R*,2*S*,5*R*)-2-Isopropyl-5-methylcyclohexyl)oxytriphenylsilyl ether ((*L*)-4).⁴⁹ Synthesized according to GP1 with 48 mg of *L*-menthol and 76 mg of triphenylsilyl chloride which yielded a white solid 120 mg, 90%; ^1H NMR (400 MHz, CDCl_3): δ ppm 7.62 (dd, $J = 7.9, 1.5$ Hz, 6H), 7.46–7.32 (m, 9H), 3.54 (td, $J = 10.1, 4.3$ Hz, 1H), 2.38 (dtd, $J = 13.9, 6.9, 2.4$ Hz, 1H), 1.93–1.82 (m, 1H), 1.62–1.47 (m, 2H), 1.39–1.07 (m, 3H), 0.88 (d, $J = 7.1$ Hz, 3H), 0.84–0.80 (m, 2H), 0.79 (d, $J = 6.0$ Hz, 3H), 0.39 (d, $J = 6.9$ Hz, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 135.6, 135.2, 129.8, 127.7, 73.9, 50.2, 45.3, 34.5, 31.6, 25.3, 22.6, 22.3, 21.4, 15.3. Optical rotation $[\alpha]_{\text{D}}^{25}$: -40.0 ($c = 0.022$) in CHCl_3 .

((1*S*,2*R*,5*S*)-2-Isopropyl-5-methylcyclohexyl)oxytriphenylsilyl ether ((*D*)-4).⁴⁹ Synthesized according to GP1 with 48 mg of *D*-menthol and 76 mg of triphenylsilyl chloride which yielded a white solid 120 mg, 90%; ^1H NMR (400 MHz, CDCl_3): δ ppm 7.62 (dd, $J = 7.9, 1.5$ Hz, 6H), 7.49–7.31 (m, 9H), 3.54 (td, $J = 10.1, 4.3$ Hz, 1H), 2.38 (dtd, $J = 13.9, 6.9, 2.4$ Hz, 1H), 1.94–1.83 (m, 1H), 1.63–1.50 (m, 2H), 1.39–1.09 (m, 3H), 0.88 (d, $J = 7.1$ Hz, 3H), 0.85–0.80 (m, 2H), 0.79 (d, $J = 6.0$ Hz, 3H), 0.38 (d, $J = 6.9$ Hz, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 135.6, 135.2, 129.8, 127.7, 73.9, 50.2, 45.3, 34.5, 31.6, 25.3, 22.6, 22.3, 21.4, 15.3. Optical rotation $[\alpha]_{\text{D}}^{25}$: +39.0 ($c = 0.02$) in CHCl_3 .

Triphenyl(((1*S*,2*R*,4*S*)-1,7,7-Trimethylbicyclo[2.2.1]heptan-2-yl)oxy)silane (7).⁵⁰ Synthesized according to GP1 with 18 mg of (-)-borneol and 24 mg of triphenylsilyl chloride which yielded a white solid 40 mg, 95%; ^1H NMR (400 MHz, CDCl_3): δ ppm 7.66–7.57 (m, 6H), 7.46–7.33 (m, 9H), 4.18 (d, $J = 9.4$ Hz, 1H), 2.39–2.27 (m, 1H), 1.98–1.87 (m, 1H), 1.77–1.64 (m, 1H), 1.34–1.18 (m, 3H), 1.01 (dd, $J = 13.2, 3.2$ Hz, 1H), 0.81 (s, 3H), 0.70 (d, $J = 6.6$ Hz, 6H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 135.6, 135.2, 129.8, 127.7, 78.6, 50.2, 47.3, 45.2, 39.4, 28.4, 26.5, 20.2, 18.8, 13.6. Optical rotation $[\alpha]_{\text{D}}^{25}$: +24.1 ($c = 0.02$) in CHCl_3 .

(*R*)-(Chroman-4-yloxy)triphenylsilyl ether ((*R*)-5).¹⁴ Synthesized according to GP1 with 23 mg of (*R*)-chromanol and 36 mg of triphenylsilyl chloride which yielded a white solid 50 mg, 81%; ^1H NMR (400 MHz, CDCl_3): δ ppm 7.66 (d, $J = 6.5$ Hz, 6H), 7.48–7.37

(m, 9H), 7.18–7.14 (m, 1H), 6.99 (d, $J = 7.2$ Hz, 1H), 6.83–6.76 (m, 2H), 4.97 (t, $J = 4.0$ Hz, 1H), 4.51–4.45 (m, 1H), 4.24–4.19 (m, 1H), 2.02–1.96 (m, 2H); ^{13}C NMR (101 MHz, CDCl_3) δ ppm 154.5, 135.5, 134.3, 130.1, 130.0, 129.2, 127.8, 124.2, 120.0, 116.7, 65.0, 62.2, 31.4. Optical rotation $[\alpha]_{\text{D}}^{25}$: +53.4 ($c = 0.031$) in CHCl_3 .

(*S*)-(Chroman-4-yloxy)triphenylsilane ((*S*)-5):¹⁴ Synthesized according to GP1 with 23 mg of (*S*)-chromanol and 36 mg of triphenylsilyl chloride which yielded a white solid 43 mg, 70%; ^1H NMR (400 MHz, CDCl_3): δ ppm 7.62 (t, $J = 12.8$ Hz, 6H), 7.41 (dt, $J = 24.3, 7.2$ Hz, 9H), 7.14 (t, $J = 7.7$ Hz, 1H), 6.97 (d, $J = 7.5$ Hz, 1H), 6.78 (dd, $J = 17.2, 8.0$ Hz, 2H), 4.96 (t, $J = 4.0$ Hz, 1H), 4.46 (td, $J = 10.4, 3.1$ Hz, 1H), 4.24–4.15 (m, 2H); ^{13}C NMR (101 MHz, CDCl_3) δ ppm 154.6, 135.6, 134.5, 130.2, 130.1, 129.3, 128.0, 124.3, 120.1, 116.8, 65.1, 62.2, 31.5. Optical rotation $[\alpha]_{\text{D}}^{25}$: –49.0 ($c = 0.031$) CHCl_3 .

(*R*)-4,4-Dimethyl-3-((triphenylsilyloxy)dihydrofuran-2(3*H*)-one ((*R*)-6):¹⁵ Synthesized according to GP1 with 6 mg of (*R*)-pantolactone and 10 mg of triphenylsilyl chloride which yielded a white solid 12 mg, 70%; ^1H NMR (400 MHz, CDCl_3): δ 7.72 (d, $J = 6.6$ Hz, 6H), 7.48–7.37 (m, 9H), 4.15 (s, 1H), 3.94 (d, $J = 8.9$ Hz, 1H), 3.76 (d, $J = 8.9$ Hz, 1H), 1.18 (s, 3H), 0.86 (s, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ ppm 175.2, 135.7, 133.4, 130.4, 127.9, 75.5, 41.1, 22.6, 19.7. Optical rotation $[\alpha]_{\text{D}}^{25}$: +8.2 ($c = 0.84$) CHCl_3 .

((*1R,2S,5R*)-2-Isopropyl-5-methylcyclohexyl)oxy)tri(naphthalen-2-yl)silane ((*L*)-8). Synthesized according to GP2 with 51 mg of *l*-menthol and 125 mg of trinaphthylsilane which yielded a white solid 180 mg, 97%; mp range = 102–105 °C; ^1H NMR (400 MHz, CDCl_3): δ 8.22 (s, 3H), 7.80 (ddd, $J = 14.8, 9.2, 4.5$ Hz, 12H), 7.50 (dtd, $J = 14.7, 6.9, 1.3$ Hz, 6H), 3.68 (td, $J = 10.3, 4.3$ Hz, 1H), 2.56 (dtd, $J = 13.9, 6.9, 2.4$ Hz, 1H), 2.03 (d, $J = 11.9$ Hz, 1H), 1.60–1.54 (m, 2H), 1.51–1.12 (m, 3H), 0.93 (d, $J = 7.1$ Hz, 3H), 0.85 (dd, $J = 19.6, 10.9$ Hz, 2H), 0.78 (d, $J = 6.4$ Hz, 3H), 0.41 (d, $J = 6.9$ Hz, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 137.1, 134.2, 132.9, 132.7, 131.4, 128.5, 127.8, 127.1, 126.9, 126.0, 74.3, 50.3, 45.5, 34.5, 31.6, 25.5, 22.6, 22.3, 21.4, 15.6. Optical rotation $[\alpha]_{\text{D}}^{25}$: –24.9 ($c = 0.03$) CHCl_3 HRMS: (ESI) calculated for ($\text{C}_{40}\text{H}_{40}\text{OSi}^+$) (M^+): 564.2848, observed: 564.2850. IR (neat, cm^{-1}) 3049, 2953, 2921, 1589, 1250, 1456, 1272, 1083, 853, 816, 740.

((*1S,2R,5S*)-2-Isopropyl-5-methylcyclohexyl)oxy)tri(naphthalen-2-yl)silane ((*D*)-8). Synthesized according to GP2 with 51 mg of *D*-menthol and 125 mg of trinaphthylsilane which yielded a white solid 183 mg, 97%; mp range = 102–105 °C; ^1H NMR (400 MHz, CDCl_3): δ 8.22 (s, 3H), 7.80 (ddd, $J = 14.8, 9.2, 4.5$ Hz, 12H), 7.50 (dtd, $J = 14.7, 6.9, 1.3$ Hz, 6H), 3.68 (td, $J = 10.3, 4.3$ Hz, 1H), 2.56 (dtd, $J = 13.9, 6.9, 2.4$ Hz, 1H), 2.03 (d, $J = 11.9$ Hz, 1H), 1.60–1.54 (m, 2H), 1.51–1.12 (m, 3H), 0.93 (d, $J = 7.1$ Hz, 3H), 0.85 (dd, $J = 19.6, 10.9$ Hz, 2H), 0.78 (d, $J = 6.4$ Hz, 3H), 0.41 (d, $J = 6.9$ Hz, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 137.1, 134.2, 132.9, 132.7, 131.4, 128.5, 127.8, 127.1, 126.9, 126.0, 74.3, 50.3, 45.5, 34.5, 31.6, 25.5, 22.6, 22.3, 21.4, 15.6. Optical rotation $[\alpha]_{\text{D}}^{25}$: +24.0 ($c = 0.03$) CHCl_3 ; HRMS: (ESI) calculated for ($\text{C}_{40}\text{H}_{40}\text{OSi}^+$) (M^+): 564.2848, observed: 564.2851. IR (neat, cm^{-1}) 3050, 2952, 2918, 1589, 1456, 1272, 1082, 852, 815, 739.

(*R*)-(Chroman-4-yloxy)tri(naphthalen-2-yl)silane ((*R*)-9). Synthesized according to GP2 with 36 mg of (*R*)-chromanol and 85 mg of trinaphthylsilane which yielded a white solid 125 mg, 96%; mp range = 110–112 °C; ^1H NMR (400 MHz, CDCl_3): δ ppm 8.22 (s, 3H), 8.22 (s, 6H), 7.79 (dd, $J = 7.5, 4.8$ Hz, 6H), 7.51 (ddd, $J = 14.9, 13.6, 6.8$ Hz, 6H), 7.21–7.14 (m, 1H), 7.11 (d, $J = 7.6$ Hz, 1H), 6.84 (d, $J = 8.1$ Hz, 1H), 6.77 (t, $J = 7.4$ Hz, 1H), 5.11 (t, $J = 4.0$ Hz, 1H), 4.58 (td, $J = 10.7, 2.7$ Hz, 1H), 4.25 (dt, $J = 8.5, 4.1$ Hz, 1H), 2.16–1.94 (m, 2H); ^{13}C NMR (101 MHz, CDCl_3) δ ppm 154.7, 137.2, 134.3, 132.9, 131.9, 131.1, 130.2, 129.4, 128.5, 127.8, 127.4, 127.1, 126.1, 124.2, 120.1, 116.8, 65.4, 62.3, 31.6. Optical rotation $[\alpha]_{\text{D}}^{25}$: +22.0 ($c = 0.26$) CHCl_3 ; HRMS: (ESI) calculated for ($\text{C}_{39}\text{H}_{30}\text{O}_2\text{Si}^+$) (M^+): 558.2015, observed: 558.2050. IR (neat, cm^{-1}) 2974, 2928, 1736, 1590, 1458, 1387, 1263, 1142, 1092, 962, 858, 818, 742.

(*R*)-4,4-Dimethyl-3-((tri(naphthalen-2-yl)silyloxy)dihydrofuran-2(3*H*)-one ((*R*)-10). Synthesized according to GP2 with 29 mg of (*R*)-pantolactone and 82 mg of trinaphthylsilane which yielded a white

solid 110 mg, 95%; mp range = 70–71 °C; ^1H NMR (400 MHz, CDCl_3): δ 8.24 (s, 3H), 7.91 (t, $J = 7.3$ Hz, 6H), 7.85 (d, $J = 8.0$ Hz, 3H), 7.78 (dd, $J = 8.2, 1.0$ Hz, 3H), 7.60–7.49 (m, 6H), 4.25 (dd, $J = 5.1, 3.3$ Hz, 1H), 3.86–3.80 (m, 2H), 1.23 (s, 3H), 0.94 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ ppm 137.1, 134.3, 132.9, 131.7, 131.0, 128.5, 127.8, 127.4, 127.1, 126.2, 80.5, 78.7, 75.0, 43.3, 24.8, 19.6. Optical rotation $[\alpha]_{\text{D}}^{25}$: +17.6 ($c = 0.031$) CHCl_3 HRMS: (ESI) calculated for ($\text{C}_{36}\text{H}_{30}\text{O}_3\text{Si}^+$) (M^+): 538.1964, observed: 538.1965. IR (neat, cm^{-1}) 3051, 2959, 2928, 1733, 1590, 1464, 1272, 1087, 1021, 951, 853, 818, 741.

Molecular Modeling Information. Conformer searches were carried out using the Monte Carlo for Complex Chemical System (MCCCS) Towhee⁵¹ plug-in built into the Scienomics Materials Processes and Simulations (MAPS) platform.⁵² The conformers with energies within 2 kcal/mol relative to the lowest energy conformer were selected, and the structures were optimized using DFT (B3LYP) with 6-311++** basis set in Spartan.⁴⁵ For all optimized structures, frequency calculations were carried out at the same level of theory to confirm that the conformers were stable. A Boltzmann distribution of the selected conformers was calculated on the basis of ΔG and $T = 298$ K.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b01137.

CD spectra, crystal structure data, molecular modeling information, and NMR spectra (PDF)
CIF data for (*S*)-5, (*R*)-5, and 7 (CIF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

- Jacobsen, E. N.; Pfaltz, A.; Yamamoto, H. *Comprehensive Asymmetric Catalysis I-III*; Springer-Verlag: New York, 1999; Vols. 1–3.
- Noyori, R. *Angew. Chem., Int. Ed.* **2002**, *41*, 2008.
- Ooi, T.; Maruoka, K. *Angew. Chem., Int. Ed.* **2007**, *46*, 4222.
- Wolf, C.; Bentley, K. W. *Chem. Soc. Rev.* **2013**, *42*, 5408.
- Labuta, J.; Hill, J. P.; Ishihara, S.; Hanyková, L.; Ariga, K. *Acc. Chem. Res.* **2015**, *48*, 521.
- Katoono, R.; Kawai, H.; Fujiwara, K.; Suzuki, T. *J. Am. Chem. Soc.* **2009**, *131*, 16896.
- Ściebura, J.; Skowronek, P.; Gawroński, J. *Angew. Chem., Int. Ed.* **2009**, *48*, 7069.
- Ściebura, J.; Gawroński, J. *Chem. - Eur. J.* **2011**, *17*, 13138.
- Katoono, R.; Kawai, H.; Ohkita, M.; Fujiwara, K.; Suzuki, T. *Chem. Commun.* **2013**, *49*, 10352.
- Katoono, R.; Fujiwara, K.; Suzuki, T. *Chem. Commun.* **2014**, *50*, 5438.
- Prusinowska, N.; Bendzińska-Berus, W.; Jelecki, M.; Rychlewska, U.; Kwit, M. *Eur. J. Org. Chem.* **2015**, *2015*, 738.

- (12) Prusinowska, N.; Bendzińska-Berus, W.; Szymkowiak, J.; Warzajtis, B.; Gajewy, J.; Jelecki, M.; Rychlewska, U.; Kwit, M. *RSC Adv.* **2015**, *5*, 83448.
- (13) Skowronek, P.; Ścianowski, J.; Pacula, A. J.; Gawroński, J. *RSC Adv.* **2015**, *5*, 69441.
- (14) Sheppard, C. L.; Taylor, J. L.; Wiskur, S. L. *Org. Lett.* **2011**, *13*, 3794.
- (15) Clark, R. W.; Deaton, T. M.; Zhang, Y.; Moore, M. I.; Wiskur, S. L. *Org. Lett.* **2013**, *15*, 6132.
- (16) Wang, L.; Akhiani, R. K.; Wiskur, S. L. *Org. Lett.* **2015**, *17*, 2408.
- (17) Kagan, H. B.; Fiaud, J. C. In *Topics in Stereochemistry*; Ernest, L., Wilen, S. H., Eds.; John Wiley and Sons: New York, 1988; Vol. 18, p 249.
- (18) Keith, J. M.; Larrow, J. F.; Jacobsen, E. N. *Adv. Synth. Catal.* **2001**, *343*, 5.
- (19) Robinson, D. E. J. E.; Bull, S. D. *Tetrahedron: Asymmetry* **2003**, *14*, 1407.
- (20) Vedejs, E.; Jure, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 3974.
- (21) Pellissier, H. *Adv. Synth. Catal.* **2011**, *353*, 1613.
- (22) Birman, V. B.; Li, X. M. *Org. Lett.* **2006**, *8*, 1351.
- (23) Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1973**, *95*, 1535.
- (24) Boettcher, R. J.; Gust, D.; Mislow, K. *J. Am. Chem. Soc.* **1973**, *95*, 7157.
- (25) Mislow, K. *Acc. Chem. Res.* **1976**, *9*, 26.
- (26) Hummel, J. P.; Zurbach, E. P.; Dicarolo, E. N.; Mislow, K. *J. Am. Chem. Soc.* **1976**, *98*, 7480.
- (27) Wuts, P. G. M.; Greene, T. W. *Protective Groups in Organic Synthesis*, 3rd ed.; Wiley-Interscience: New York, 1999.
- (28) Cottrell, T. L. *The Strengths of Chemical Bonds*, 2nd ed.; Butterworths: London, 1958.
- (29) Lightner, D. A.; Gurst, J. E. *Organic Conformational Analysis and Stereochemistry from Circular Dichroism Spectroscopy*; Wiley-VCH: New York, 2000.
- (30) Berova, N.; Nakanishi, K.; Woody, R. W. *Circular Dichroism-Principles and Applications*, 2nd ed.; Wiley-VCH: New York, 2000.
- (31) Berova, N.; Polavarapu, P. L.; Nakanishi, K.; Woody, R. W. *Comprehensive Chiroptical Spectroscopy*; John Wiley & Sons: New York, 2012; Vols. 1–2.
- (32) Sreerama, N.; Woody, R. W. *Anal. Biochem.* **2000**, *287*, 252.
- (33) Hall, V.; Sklepari, M.; Rodger, A. *Chirality* **2014**, *26*, 471.
- (34) Woody, R. W. *Biomed. Spectrosc. Imaging* **2015**, *4*, 5.
- (35) Berova, N.; Di Bari, L.; Pescitelli, G. *Chem. Soc. Rev.* **2007**, *36*, 914.
- (36) Pescitelli, G.; Di Bari, L.; Berova, N. *Chem. Soc. Rev.* **2011**, *40*, 4603.
- (37) Blackwell, J. M.; Foster, K. L.; Beck, V. H.; Piers, W. E. *J. Org. Chem.* **1999**, *64*, 4887.
- (38) Crabbe, P. *Optical Rotatory Dispersion and Circular Dichroism In Organic Chemistry*; Holden-Day: San Francisco, 1965.
- (39) Kalsi, P. S. *Spectroscopy of Organic Compounds*; New Age International: New Delhi, 2007.
- (40) Barbieri, G.; Andreetti, G. D.; Bocelli, G.; Sgarabotto, P. J. *Organomet. Chem.* **1979**, *172*, 285.
- (41) Beckers, H.; Brauer, D. J.; Burger, H.; Wilke, C. J. *J. Organomet. Chem.* **1988**, *356*, 31.
- (42) Shankar, R.; Joshi, A.; Upreti, S. *Polyhedron* **2006**, *25*, 2183.
- (43) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648.
- (44) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1988**, *37*, 785.
- (45) In *Spartan 10, Program for Calculation of Molecular Properties*; Wavefunction Inc.: Irvine, CA, 2015.
- (46) Dinitto, J. M.; Kenney, J. M. *Appl. Spectrosc.* **2012**, *66*, 180.
- (47) Savitzky, A.; Golay, M. J. E. *Anal. Chem.* **1964**, *36*, 1627.
- (48) Hayase, S.; Onishi, Y.; Suzuki, S.; Wada, M. *Macromolecules* **1986**, *19*, 968.
- (49) Lage, M. L.; Bader, S. J.; Sa-ei, K.; Montgomery, J. *Tetrahedron* **2013**, *69*, 5609.
- (50) Alberti, A.; Guerra, M.; Pedulli, G. F. *J. Am. Chem. Soc.* **1981**, *103*, 6604.
- (51) Martin, M. G. *Mol. Simul.* **2013**, *39*, 1184.
- (52) *Materials and Processes Simulations (MAPS)*; Scienomics SARL, Paris, France, 2004–2013.