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Preparation of Strained Axially Chiral (1,5)Naphthalenophanes by Photo-dehydro-Diels−Alder Reaction

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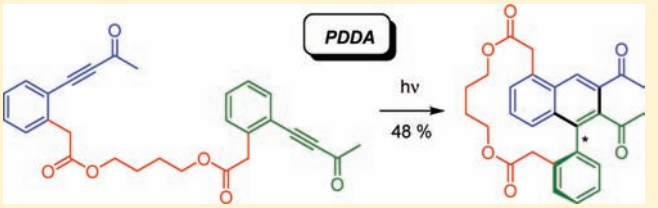
Supporting Information

ABSTRACT: The preparation of 10 (1,5)naphthalenophanes (**10a**−**j**) by photo-dehydro-Diels−Alder (PDDA) reaction is described. Owing to hindered rotation around the biaryl axis, compounds **10** are axially chiral and the separation of enantiomers by chiral HPLC was demonstrated in three cases (**10a,b, e**). The absolute configuration of the isolated enantiomers could be unambiguously determined by comparison of calculated and measured circular dichroism (CD) spectra. Furthermore, we analyzed ring strain phenomena of (1,5)naphthalenophanes **10**. Depending on the length of the linker units, one can distinguish three classes of naphthalenophanes. Compounds **10a**−**c** are highly strained (E_{STR} = 7−31 kcal/mol), and the strain is caused by small bond angles in the linker unit and deformation of the naphthalene moiety. Another type of strain is observed if the linker unit becomes relatively long (**10g,h**) originating from transannular interactions and is comparable with the well-known strain of medium sized rings. The naphthalenophanes **10d**−**f** with a linker length of 10−14 atoms are only marginally strained. To clearly discriminate the different sources of strain, we defined two geometrical parameters (average central dihedral angle δ_C and naphthalene thickness D_N) and demonstrated that they are well-suited to indicate naphthalene deformation of our naphthalenophanes **10** as well as of ten model naphthalenophanes (**I**−**X**) with different linker lengths and linking positions.

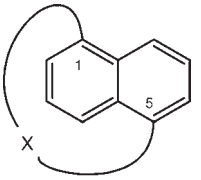


INTRODUCTION

The synthesis of highly strained molecules is enjoying great interest since many decades and is still a challenge for preparative chemists.[1] This interest has different sources. On the one hand, many naturally occurring compounds with biological activity have a highly strained molecular structure, and the total synthesis of these compounds requires a repertoire of special methods. On the other hand, highly strained molecules are unique objects for studying unusual bonding conditions combined with high chemical reactivity. Furthermore, strained molecules exhibit uncommon physical properties and interesting applications as functional molecules or in material science may be expected.

Molecular strain originates from bonding conditions (bond length, bond angles, and dihedral angles) that deviate more or less from their equilibrium values in unstrained molecules. This may be due to steric hindrance or cyclic structures prohibiting strain release by molecular topology. In the latter case, one refers to ring strain as a special case of molecular strain. Besides small rings (three- and four-membered rings) and unusual connectivity modes (e.g., propellanes or paddlanes), cyclophanes[2] are often characterized by high ring strain.

Cyclophanes are molecules consisting of an aromatic unit (e.g., benzene, naphthalene) and a chain (which may contain further aromatic units) forming a bridge between two nonadjacent positions of the aromatic unit. If the aromatic unit is a naphthalene moiety, these compounds are called naphthalenophanes,[3] at which the link positions are prefixed in parentheses, e.g. (1,5)naphthaleno-phanes **A** (see Figure 1).[4]



A

Figure 1. (1,5)Naphthalenophanes.

Although (1,5)naphthalenophanes were first described already more than 70 years ago by Lüttringhaus,[5] there are only a limited number of reports about synthetic access to this compound class. Particularly [*k*](1,5)naphthalenophanes with smaller linker units as those described in this paper ($k \leq 16$) scarcely appear in the literature. Beside the pioneering work by Haenel,[6] only 15 other articles were published in the last 80 years.[7]

To the best of our knowledge, all hitherto reported synthetic routes to (1,5)naphthalenophanes are based on linking the positions 1 and 5 of an already existing naphthalene moiety. This approach is limited to naphthalenophanes with low or at best medium ring strain, but it should be difficult to prepare target compounds with high ring strain in this way. On the other hand, photochemical methods are perfectly convenient for the

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preparation of highly strained molecules because the excitation energy usually overcompensates the strain buildup.

In continuation of our previous work concerning the photo-dehydro-Diels–Alder (PDDA) reaction,[8] we have investigated whether this reaction provides an access to highly strained (1,5)naphthalenophanes.[9] In contrast to the thermally activated Diels–Alder reaction, the PDDA reaction does not proceed concerted but over several intermediates. Starting from an arylynone **B** and an alkyne **C** (which is also an arylynone in most cases and may be identical with **B**), a 1,4-diradical **D** is formed after photochemical excitation (the role of spin state is neglected here). The ring closure occurs by an attack of one of the radical centers at the opposite aromatic ring giving cyclic allene **E**. In the final step, naphthalenes **F** are formed by hydrogen migration (which is mediated by the solvent in most cases, Scheme 1).[8c–8e] It should be noted that R should be an acyl group because the PDDA reaction then takes place at a longer excitation wavelength (>300 nm) compared with R = alkyl.

On the basis of this mechanism, it should be possible to obtain (1,5)naphthalenophanes, such as **G**, by irradiation of compounds **H**, in which two arylynones are linked by a chain X (Scheme 1). As a special feature, compounds **G** contain a chirality axis (clarified by an asterisk in Scheme 1) and the enantiomers should be separable. The unique combination of axial chirality, a relatively rigid molecular structure and the cavity caused by the cyclophane structure give reason to expect very interesting applications of such compounds in the time to come, e.g. as catalysts or as components in supramolecular assemblies.

Herein we describe the successful synthesis of various (1,5)naphthalenophanes of type **G**, which are partly highly strained. Furthermore, we will report on optical and chiroptical properties as well as calculations of the ring strain of this new compound class.

Scheme 1. Photo-dehydro-Diels–Alder Reaction (Left) and Retrosynthetic Route from (1,5)-Naphthalenophanes G to H

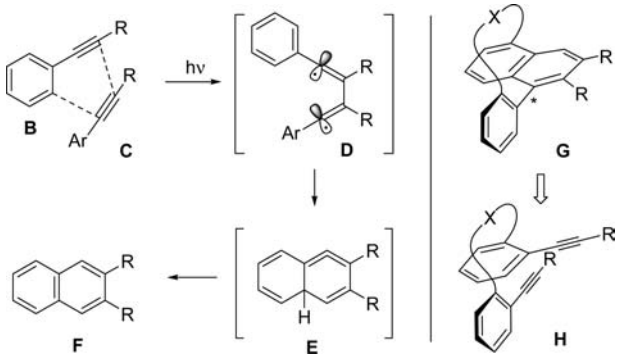


Table 1. Yields and Conditions of the Three-Step Synthesis of Bis-ynones 5a–f

	n	*m*	S-1[a]	S-2[a]	S-3[a]	M-1[b]	M-2[b]	*N*[c]
a	0	2	65	65	69	DIC/DMAP	Dess–Martin	6
b	1	2	62	99	92	DIC/DMAP	Dess–Martin	8
c	0	4	36	81	72	DIC/DMAP	Dess–Martin	8
d	1	4	56	99	69	H_2SO_4/ DCM	Dess–Martin	10
e	2	2	52	–	46[d]	DIC/HOBt	Dess–Martin	10
f	2	4	44	89	60	DIC	Swern	12

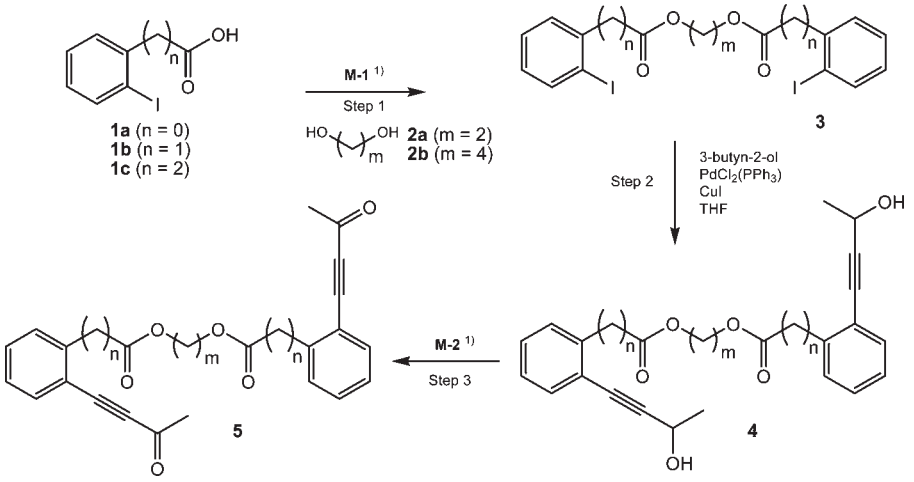
[a] Yields in percent of steps 1–3. [b] Methods M-1, M-2; see Scheme 1. [c] Number of chain atoms, $N = m + 2n + 4$. [d] Steps S-2, S-3.

RESULTS AND DISCUSSION

1. Synthesis of (1,5)Naphthalenophanes of Type G. Our three-step sequence to the reactants for the PDDA reaction commences with 2-iodobenzoic acid **1a**, 2-iodophenyl acetic acid **1b** (both are commercially available), and 3-(2-iodophenyl)-propionic acid **1c**.[10] After esterification with different diols **2**, the obtained diesters **3** are subjected to a twofold Sonogashira-coupling[11] with 3-butyn-2-ol providing the bis-propargyl alcohols **4** as a mixture of diastereomers. In the subsequent Dess–Martin[12] or Swern[13] oxidation, these diols are converted to bis-ynones **5**. The yields of these three steps are almost always good to excellent (Scheme 2, Table 1). In the following, the chain linking the two benzene rings is referred to as "linker".

In the case of bis-ynones **5g–j** with a longer linker ($N = 13–16$), another route proved to be more advantageous. It differs from the route described for **5a–f** in that initially the ynone moiety is installed and afterward the linker is completed. Starting

Scheme 2. Synthesis of Bis-ynones 5a–f[a]



[a] For M-1 and M-2, see Table 1.

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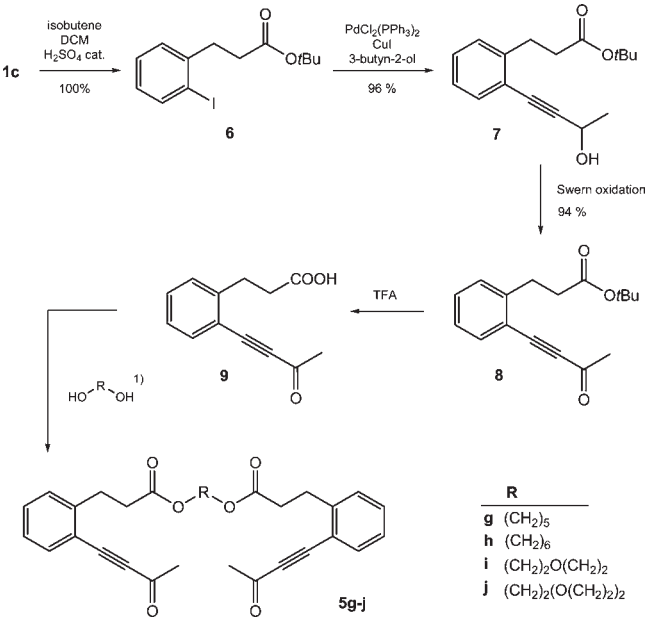
with 3-(2-iodophenyl)-propionic acid **1c**, the carboxylic group is protected as *tert*-butyl ester (**6**), followed by Sonogashira coupling with 3-butyn-2-ol (**7**), Swern oxidation to ynone **8**, and deprotection with trifluoroacetic acid, providing carboxylic acid **9**. The bis-ynones **5g**−**j** are obtained by esterification with different diols (Scheme 3, Table 2).

Table 2. Yields and Conditions of the Synthesis of Bis-ynones 5g−j

	R	esterification	yields [%]	N[a]
g	$(CH_2)_5$	DCC/DCM	78	13
h	$(CH_2)_6$	$Boc_2O/MgCl_2$/DCM	33	14
i	$(CH_2)_2O(CH_2)_2$	$Boc_2O/MgCl_2$/DCM	64	13
j	$(CH_2)_2(O(CH_2)_2)_2$	$Boc_2O/MgCl_2$/DCM	64	16

[a] Number of chain atoms.

Scheme 3. Synthesis of Bis-ynones 5g−j[a]



[a] See Table 2.

Upon irradiation (λ_{EXC} > 300 nm, pyrex vessel) in *tert*-butanol bis-ynones **5** smoothly undergo a PDDA reaction to [*k*](1,5)-naphthalenophanes **10** (Scheme 4, $k = N + 2$; see Tables 1−3). It should be mentioned that we used the optimized reaction conditions previously reported for similar PDDA reactions.[8d] Despite the rather low yields, the naphthalenophanes **10** were the sole isolable products. The remaining amount of the reactants underwent unselective decomposition.

The structure of products **10** was unambiguously proven by X-ray structure of compounds **10b** and **10g** (Figure 2, for comparison the calculated structure of **10a** is also depicted).[14] In **10b**, a [10](1,5)naphthalenophane, the naphthalene moiety is strongly distorted indicating a considerable ring strain whereas the nearly planar naphthalene moiety in the [15]-(1,5)naphthalenophane **10g** verifies a less strained molecular skeleton. Thus, the distortion of the naphthalene moiety is a sensitive indicator for ring strain of (1,5)naphthalenophanes (see section 4).

2. UV Absorption and Luminescence Properties. In the face of the above-mentioned ring strain of (1,5)naphthalenophanes **10** with shorter linkers ($k \leq 10$), we investigated the UV absorption and luminescence properties of these compounds to find out whether a systematic trend occurs depending on the linker length. We chose **10a**, **10b**, and **10e** as a typical set of (1,5)naphthalenophanes with increasing *k*-values ($k = 8, 10, 12$). As shown in Figure 3, all three compounds show absorption bands in three regions: (A) 220−260, (B) 280−310, and (C) 330−360 nm. Whereas in the spectra of **10b** and **10e**, a clear vibrational fine structure is discernible, the UV spectrum of **10a** is considerably less structured. Furthermore, the molar extinction coefficient decreases with decreasing linker length. Particularly remarkable is the decrease of the C-band from log $\varepsilon_{340} = 3.4$ (**10e**) to 2.9 (**10a**). Obviously, this phenomenon is caused by a perturbation of the π-conjugation of the naphthalene moiety by distortion (for details, see the Supporting Information (SI)).

Compounds **10a**−**j** show a negligible luminescence at room temperature, pointing to a very efficient intersystem crossing

Scheme 4. PDDA Cyclization of Bis-ynones 5 to [*k*](1,5)Naphthalenophanes 10

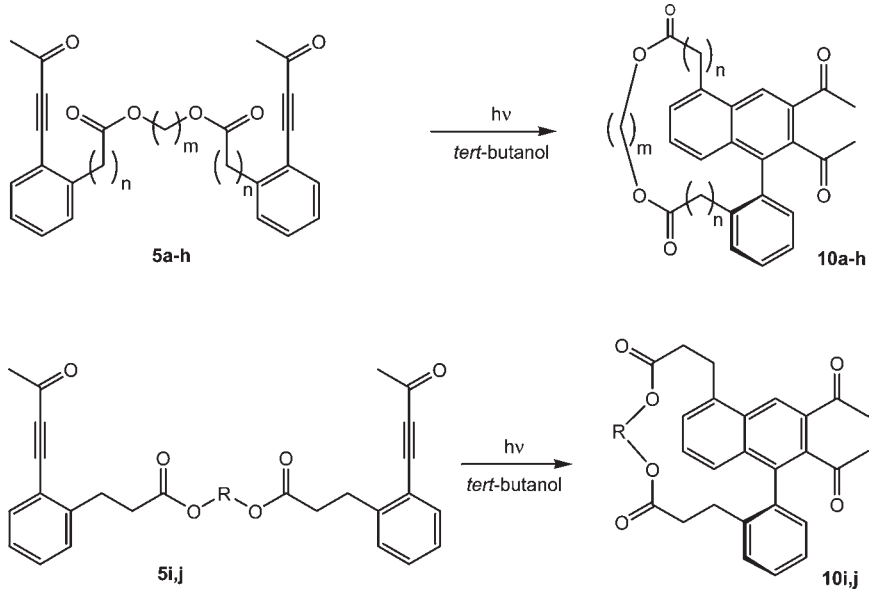


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Table 3. Yields of [*k*](1,5)Naphthalenophanes 10

	k^a	yield [%]
a	8	6
b	10	15
c	10	16
d	12	48
e	12	37
f	14	38
g	15	29
h	16	30
i	15	41
j	18	50

[a] $k = N + 2$.

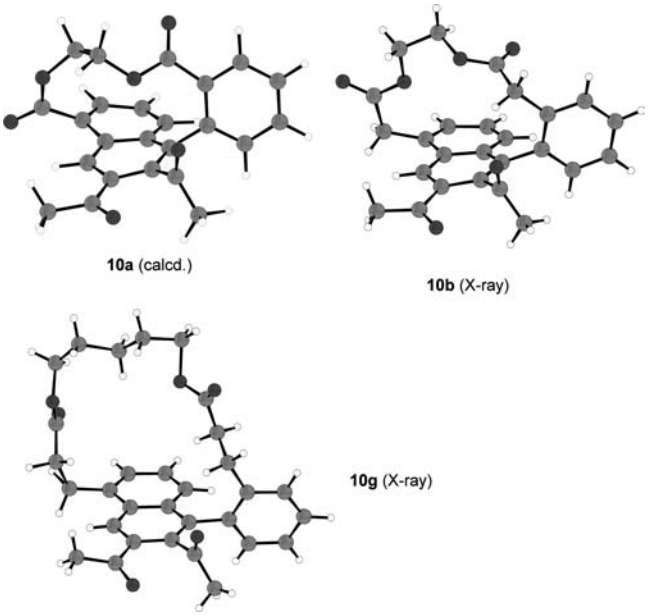

Figure 2. Calculated structure of **10a** (conformer 2, see the SI) and X-ray crystal structures of **10b** and **10g**.

(ISC) to the triplet state. This behavior was already previously observed with compounds having a 1-aryl-2-acyl-naphthalene substitution pattern.[8a] An overlap between the lone pair orbitals of the carbonyl oxygen and the π-system of the aryl ring obviously facilitates the ISC from S_1 ($n \rightarrow \pi^*$) to T_1 ($\pi \rightarrow \pi^*$) state by efficient spin−orbit coupling (Figure 4).

By embedding compounds **10** in a frozen EPA matrix (EPA = diethylether/*i*-pentane/ethanol 5:2:1) at 77 K, we observed an intense phosphorescence, which is consistent with the above postulated efficient ISC. The phosphorescence spectra of **10a**, **10b**, and **10e** are exemplarily depicted in Figure 5. The short-wavelength 0−0-transition of these spectra is blue-shifted with increasing length of the linker, i.e. the triplet energy is decreased with increasing ring strain. This observation is consistent with the idea that growing distortion of the naphthalene moiety stabilizes the triplet state because diradical contributions gain in importance.

The phosphorescence maxima and triplet energies of compounds **10** (except for **10i,j**) are summarized in Table 4.

3. Separation of Enantiomers and CD-Spectroscopy. A special structural feature of (1,5)naphthalenophanes **10** is the

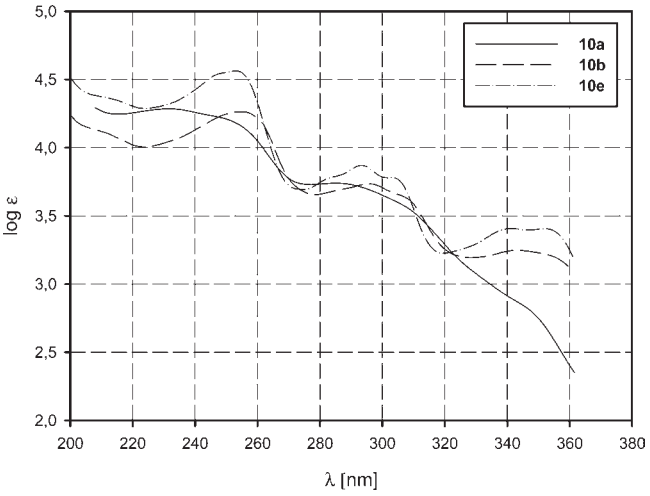

Figure 3. UV spectra of (1,5)naphthalenophanes **10a**, **10b**, and **10e** in acetonitrile.

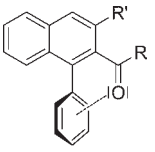

Figure 4. $n-\pi$ overlap, facilitating the ISC to the triplet state.

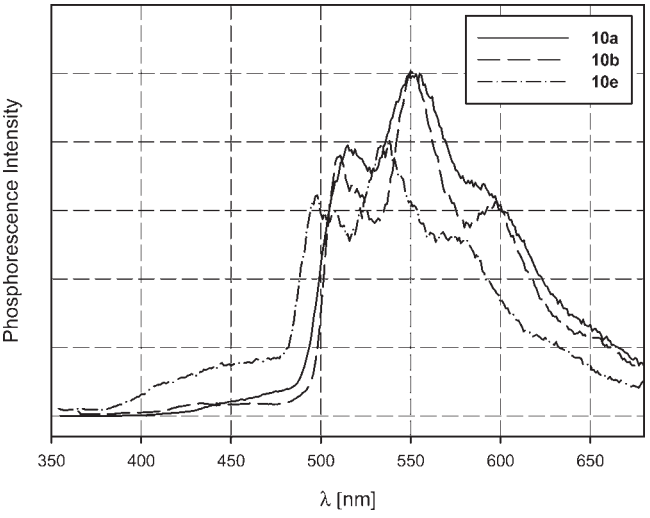

Figure 5. Phosphorescence spectra of (1,5)naphthalenophanes **10a**, **10b**, and **10e** in EPA at 77 K.

presence of a chirality axis. In view of the substitution pattern, the barrier for the rotation around this axis should be high enough at room temperature to separate the enantiomers.[15] To prove this hypothesis and to investigate the chiroptical properties of the individual enantiomers, we performed various chiral HPLC runs on different chiral stationary phases using different solvent mixtures. The best results were obtained with a Chiralcel OD-H column and a hexane/*i*-propanol (100:15) mixture as mobile phase. The recorded chromatograms for compounds **10a**, **10b**, and **10e** as well as the respective resolution *R* and separation factors α are shown in Figure 6 (**10h** was also separated. For details, see the SI). The first eluated enantiomers were called **E1**

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Table 4. Phosphorescence Maxima and Triplet Energies of [*k*](1,5)Naphthalenophanes 10

	k^a	0−0-transition [nm]	triplet energy [kcal/mol]
a	8	515	57.9
b	10	511	58.3
c	10	512	58.2
d	12	499	59.7
e	12	498	59.8
f	14	497	60.0
g	15	495	60.2
h	16	495	60.2

[a] For *k*, see Table 3.

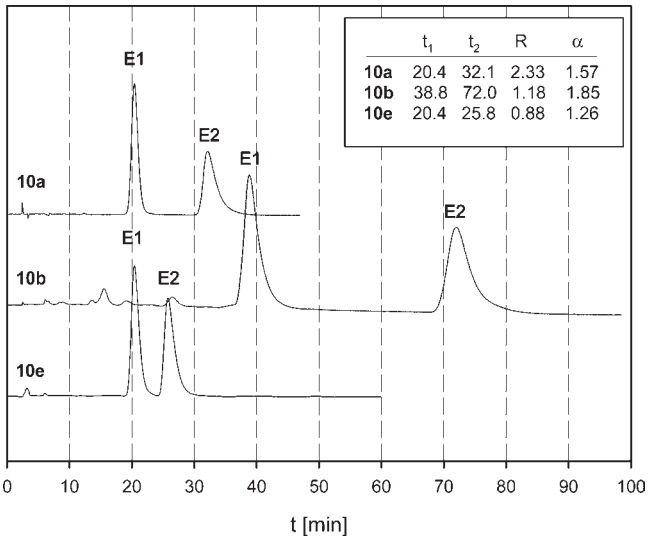

Figure 6. Separation of enantiomers of **10a**, **10b**, and **10e** by chiral HPLC (*R* = resolution, α = separation factor, t_1, t_2 = retention times of E_1, E_2, respectively, stationary phase = Chiralcel OD-H, mobile phase = hexane/*i*-propanol, 100:15).

and the second eluated enantiomers **E2**. All three compounds were baseline-separated, and the separation factors are, at least for **10a** and **10b**, excellent. With these conditions in hand, we were able to semipreparatively separate the enantiomers and investigate their chiroptical properties by means of CD-spectroscopy.

The recorded CD-spectra of first-eluated enantiomers **E1** are depicted in Figure 7. They have in common a strong Cotton effect around 220 nm, but the sign is negative for the rather strained (1,5)naphthalenophanes **10a** and **10b** and positive for **10e**. Furthermore, it is conspicuous that the CD spectra of **10b-E1** and **10e-E1** are nearly perfect mirror images. This suggests that the **E1** enantiomers of **10b** and **10e** have opposite configuration. To assign the absolute configuration to the **E1** enantiomers of **10a**, **10b**, and **10e**, we calculated the CD spectra at the density functional theory (DFT) level of theory (TD-B3LYP/6-311++G**, 30 excited states; for details, see the SI).[16] In Figure 9, the measured CD spectra are compared with the calculated CD spectra both of *M*- and *P*-enantiomers. (For definitions of the *P*- and *M*-enantiomers, see Figure 8). The comparison clearly indicates that the **E1** enantiomers of **10a** and **10b** have the same configuration (*P*) whereas **10e-E1** has the opposite configuration (*M*) in accordance with the expectation from the measured CD-spectra.

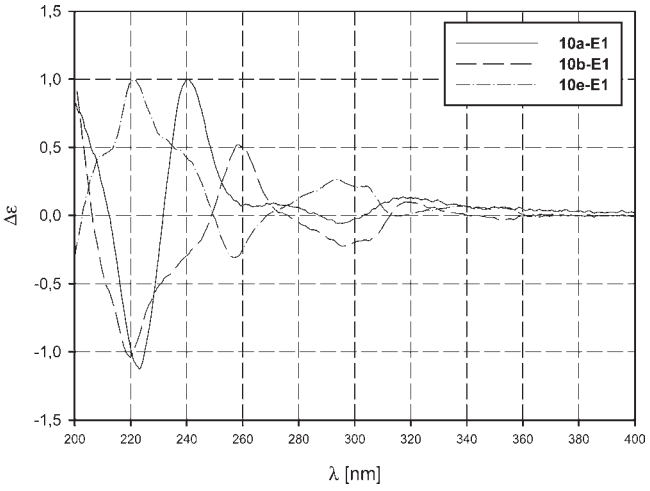

Figure 7. CD-spectra of enantiomers **E1** (see Figure 6) of **10a**, **10b**, and **10e** in acetonitrile.

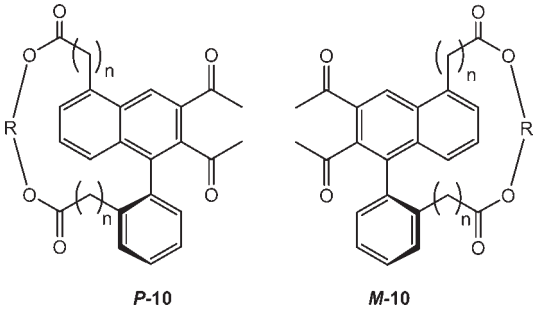

Figure 8. *P*- and *M*-enantiomers of **10**.

4. Molecular Modeling/Calculation of Ring Strain. In the preceding sections, we concluded from several experimental results that at least the (1,5)naphthalenophanes with short linking units should be highly strained. Up to now, there are only a few reports about ring strain of naphthalenophanes in the literature.[17] Due to the fundamental importance of ring strain for the physical and chemical properties of this type of compounds, we decided to undertake a systematic investigation of this phenomenon by means of quantum chemical calculations. A powerful method for the calculation of ring strain energy is the definition of an isodesmic reaction, i.e., a hypothetical reaction in which the type and number of chemical bonds cleaved in the reactants are the same as the type and number of bonds formed in the reaction products.[18] In Scheme 5, the isodesmic reactions are defined that are used for our problem. The isodesmic reactions are based on the cleavage of one bond of the diol moiety of the reactants **10** (normally the central bond [**10a**−**f**, **10h**] or a bond adjacent to the central atom [**10g**]) combined with the bond formation from acetates (**J**, **M**, **N**) to diol diacetates (**L**, **P**).

The strain energy E_{STR} can now be defined by eqs 1 and 2

$$E_{STR} = E(\mathbf{K}) + E(\mathbf{L}) - 2E(\mathbf{J}) - E(\mathbf{10a-f, 10h}) \quad (1)$$

$$E_{STR} = E(\mathbf{P}) + E(\mathbf{O}) - E(\mathbf{M}) - E(\mathbf{N}) - E(\mathbf{10g}) \quad (2)$$

The DFT calculations of strain energy E_{STR} (B3LYP/6-31G*; for details, see the SI) turned out to be in part very expensive because a large number of conformers have to be considered. The results

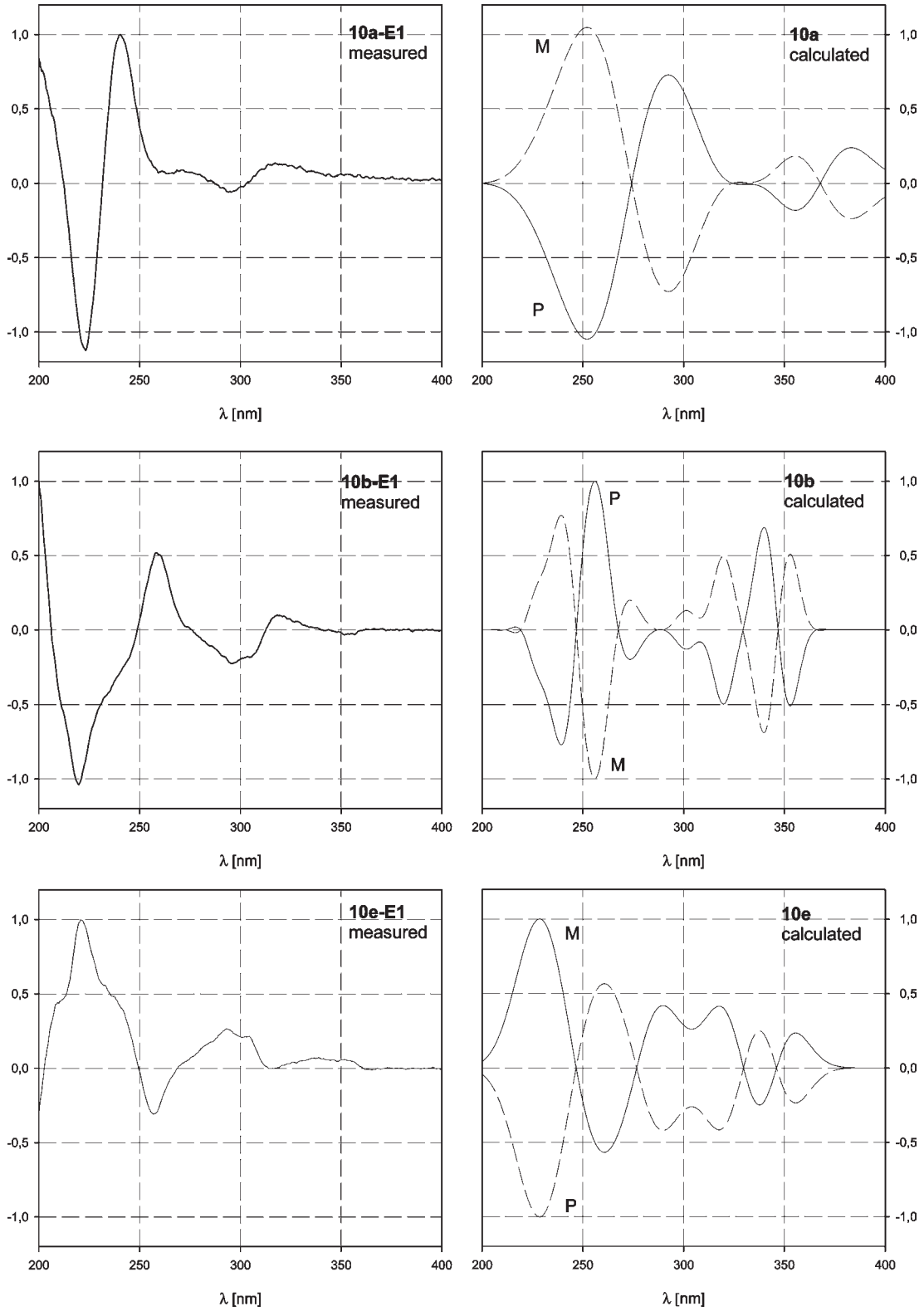

Figure 9. Comparison of the measured (left) and calculated (right) CD spectra of **10a**, **10b**, and **10e**.

of these calculations are summarized in Table 5. For compound **10a** with the shortest linker ($k = 8$), we calculated a strain energy of 31 kcal/mol, which is clearly higher than the strain energy of cyclopropane (27.6 kcal/mol)[19] and is comparable with the reported strain energies of [2.2]paracyclophane (32.0[20b] and 30.4[20g] kcal/mol). Tobe et al.[20e] reported a strain energy of 25−32.6 kcal/mol for [6](1,3)naphthalenophane, although these values are based only on semiempirical calculations. On the other hand, considerably higher strain energies were reported for [1.1]paracyclophane (90−100 kcal/mol[20f]) and [4]paracyclophane

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Scheme 5. Isodesmic Reactions for the Calculation of Ring Strain of (1,5)Naphthalenophanes 10

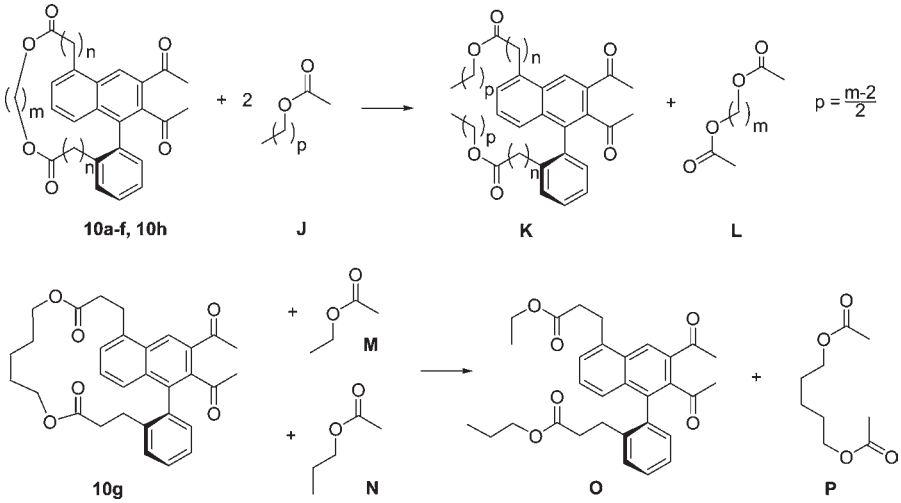

Table 5. Strain Parameters of [*k*](1,5)Naphthalenophanes 10a−h and Model Compounds I−X

	k^a	$N_{conf}{}^b$	$E_{STR}{}^c$	$E_{ND}{}^d$	$\delta_C{}^e$	$D_N{}^f$
a	8	8	31.0	7.9	164.2	0.39
b	10	24	7.1	2.4	169.8	0.24
c	10	32	11.8	3.0	172.7	0.19
d	12	32	1.1	1.0	177.0	0.07
e	12	80	2.4	1.1	177.2	0.07
f	14	92	0.0	1.1	178.3	0.04
g	15	148	7.6	1.0	179.6	0.02
h	16	44	7.0	1.0	179.2	0.02
I	8			8.8	162.4	0.43
II	10			2.8	170.4	0.23
III	6			23.6	151.0	0.65
IV	7			14.4	157.3	0.54
V	8			7.7	163.7	0.41
VI	6			21.9	154.9	0.69
VII	7			7.2	165.7	0.39
VIII	8			12.3	161.1	0.53
IX	6			6.1	171.5	0.30
X	8			1.5	176.1	0.12

[a] For *k* of **10a**−**h**, see Table 3. [b] Number of conformers to be considered (**10a**−**h** only). [c] Strain energy according to eqs 1 and 2 in kilocalories per mole (**10a**−**h** only). [d] Naphthalene deformation energy in kilocalories per mole. [e] Average central dihedral angle in degrees. [f] Thickness of naphthalene moiety in angstroms. (E_{SRT}, E_{ND}, δ_C, and D_N were calculated for the conformer with the lowest energy in each case.)

(91.3 kcal/mol[20d]). If the linker becomes longer by two atoms (**10b** and **c**), the strain energy is reduced to 7.1 and 11.8 kcal/mol, respectively, whereas naphthalenophanes **10d**−**f** exhibit only marginal ring strain. The relatively high strain energy of 7−8 kcal/mol for compounds **10g** and **h** is surprising at first glance.

At this point, we decided to illuminate the origin of the ring strain energy more precisely. As mentioned in the introduction, both the deformation of the naphthalene moiety and unfavorable bonding conditions in the linker unit contribute to the strain energy.[20] To isolate these two parts of strain, we have "cut off" the naphthalene moieties from the calculated structures (i.e., removing the acetyl groups and the linker) and saturated the free valences with hydrogen atoms. The strain energy of the resulting puckered naphthalenes was obtained by comparison with the energy of optimized perfect planar naphthalene geometry. We found that in the case of highly strained **10a** about one-fourth of the strain energy E_{SRT} arises from naphthalene deformation (E_{ND} = 7.1 kcal/mol) whereas three-fourths is caused by the linker unit. We found a similar situation for (1,5)naphthalenophanes **10b** and **c**, but the contribution of E_{ND} becomes considerably higher with the less strained compounds **10d**−**f** (the apparently inconsistent values **10f** are probably due to limits of the used model).

Because the naphthalene moiety is relatively sensitive to twisting forces, it should be possible to estimate the strain caused by naphthalene deformation by evaluating ideally one geometrical parameter. We found that two different parameters are comparably well-suited for this purpose. The first parameter δ_C is the average central dihedral angle of the naphthalene moiety as defined in Figure 10. It should be noted that it is not sufficient to evaluate only one of the central dihedral angles because the deformation caused by the (1,5)-bridge leads not only to a twist around the axis as shown in Figure 10 but also to a small pyramidalization of atoms 4a and 8a, and therefore, the central dihedral angles are not identical. The second parameter suitable for an evaluation of the naphthalene deformation is the thickness D_N. We define the thickness D_N as the minimally possible height of a cuboid surrounding all ten naphthalene carbon atoms. To evaluate the generalizability of this approach, we extended the calculations on ten model naphthalenophanes **I**−**X**, some of which are considerably more strained than compounds **10**. We were particularly interested to find out whether (1,5)naphthalenophanes without ester groups (**I**, **II**), without *o*-phenyliden group (**III**−**V**), or naphthalenophanes with other linking positions (e.g., (1,6)naphthalenophanes **VI**−**VIII** or (1,7)naphthalenophanes **IX**, **X**) also exhibit the empirical correlation found for naphthalenophanes **10**. The suitability of these two parameters δ_C and D_N is discernible by the excellent correlation with the naphthalene deformation energy E_{ND}, as depicted in Figure 11. (For calculation of E_{ND} as well as the curve fittings, see the

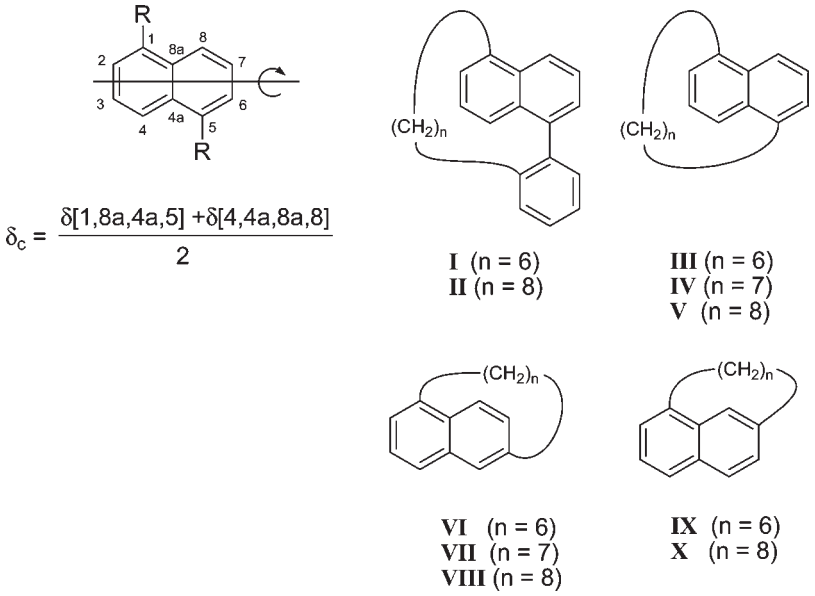

Figure 10. Definition of the average central dihedral angle δ_C and formulas of the model naphthalenophanes **I**−**X**.

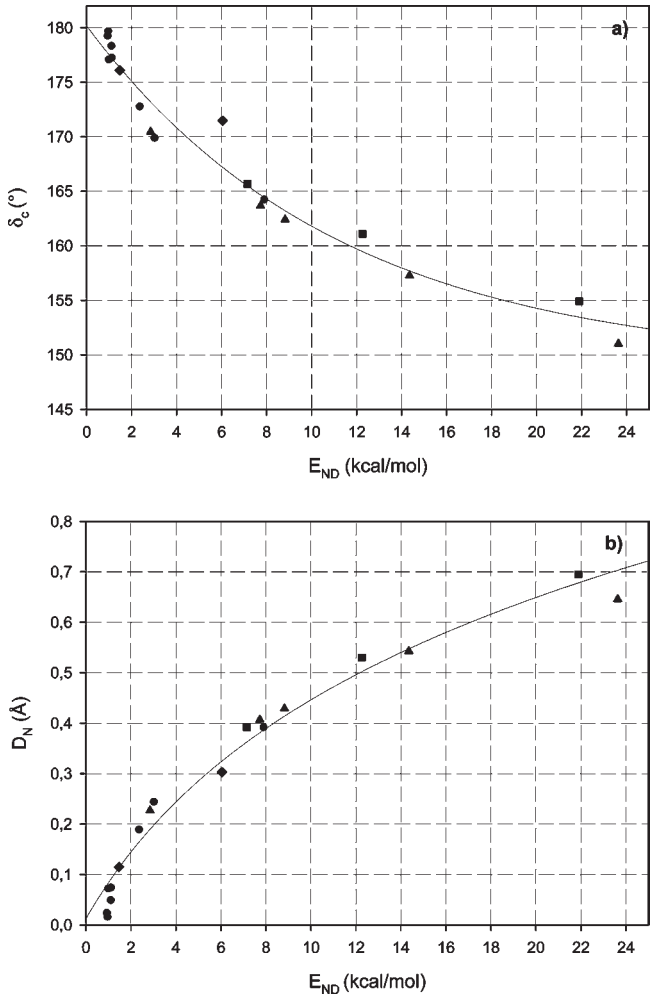

Figure 11. Correlation of the naphthalene deformation energy E_{ND} with the average central dihedral angle δ_C (a) and the naphthalene thickness D_N (b) (**10a**−**h** [circles], **I**−**V** [triangles], **VI**−**VIII** [squares], **IX**, **X** [diamonds]).

comments in the SI). Obviously, the strain energy of the naphthalene moiety caused by its deformation in naphthalenophanes is mostly independent from the positions of the linker (provided that they are not in the same benzene ring).

At last, we wish to return to the unexpected strain energies of (1.5)naphthalenophanes **10g** and **10h**. The results summarized in Table 5 indicate that this strain is solely derived from the linker but not by deformation of the naphthalene moiety. Evaluating the calculated structures of these compounds as well as the X-ray structure of **10g** reveals that in both cases some short distances of nonbonded atoms exist which obviously cause the strain. This phenomenon is closely related to the well-known ring strain of medium sized cycloalkanes.[21]

CONCLUSION

In summary, we reported on the preparation of ten (1,5)naphthalenophanes (**10a**−**j**) by photo-dehydro-Diels−Alder (PDDA) reaction. To the best of our knowledge, it is the first approach in which the naphthalene moiety is constructed only in the ring closure step of the cyclophane synthesis. Compounds **10** feature an efficient intersystem crossing (ISC) to the triplet state upon irradiation and the triplet energies could be determined from the phosphorescence spectra at 77 K. Due to hindered rotation around the biaryl axis, compounds **10** are axially chiral and the separation of enantiomers by chiral HPLC was demonstrated in three cases (**10a**,**b**,**e**). The absolute configuration of the isolated enantiomers could be unambiguously determined by comparison of calculated and measured CD spectra. In the last part we turned to analyzing ring strain phenomena of (1,5)-naphthalenophanes **10**. Depending on the length of the linker units, one can distinguish three classes of naphthalenophanes. Compounds **10a**−**c** are highly strained (E_{STR} = 7−31 kcal/mol) and the strain is caused by small bond angles in the linker unit and deformation of the naphthalene moiety. Another type of strain is observed if the linker unit becomes relatively long (**10g**,**h**) originating from transannular interactions and is comparable with the well-known strain of medium sized rings. The naphthalenophanes **10d**−**f** with a linker length of 10−14 atoms are only

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marginally strained. To clearly discriminate the different sources of strain, we defined two geometrical parameters (average central dihedral angle δ_C and naphthalene thickness D_N) and demonstrated that they are well-suited to indicate naphthalene deformation of various (*n*,*m*)naphthalenophanes (n = 1, m = 5, 6, 7) without the necessity of expensive calculations. After the successful application of the PDDA methodology to the synthesis of (1,5)naphthalenophanes, we are now investigating an extension of this approach to other substitution patterns and will report on the results in the near future.

■ ASSOCIATED CONTENT

Supporting Information. Synthetic procedures for all new compounds including analytical data and copies of ^{13}C-spectra. Details of quantumchemical calculations. CD spectroscopy, chiral HPLC, and phosphorescence measurements. This information is available free of charge via the Internet at http://pubs.acs.org/.

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