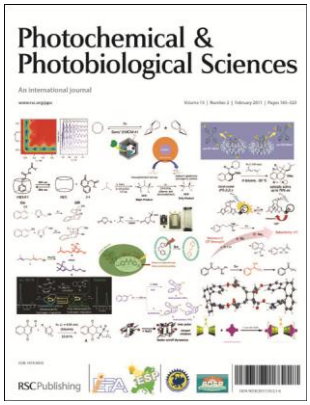

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PAPER

Chirogenic [3 + 2]-photocycloaddition reactions of 2-substituted naphthoquinones with cyclic alkenes†‡

Christiane Müller, Andreas Bauer and Thorsten Bach*

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The formal [3 + 2]-photocycloaddition of 2-hydroxy- (**2a**) and 2-amino-1,4-naphthoquinone (**2b**) to olefins was studied in various solvents aiming at a possible enantioselective reaction course. The reaction conditions were optimised for irradiation at low temperature in a nonpolar solvent employing external fluorescent lamps as irradiation sources. Best yields for the reaction of 2-hydroxy-1,4-naphthoquinone (**2a**) with 1-methyl-2-butene were obtained when using a large excess of the olefin (200 equiv.) in toluene as the solvent at an irradiation wavelength of $\lambda = 419$ nm. Under these conditions a variety of cyclic alkenes (cyclopentene, cyclohexene, dihydropyran, 1-methylcyclohex-1-ene) underwent the photocycloaddition in yields of 22–84%. Reactions with 2-hydroxy-1,4-naphthoquinone (**2a**) could be performed enantioselectively at −60 °C in toluene as the solvent employing a chiral hydrogen bonding template. The enantiomeric excess (≤11%) remained low, however. Possible reasons for this lack of selectivity are discussed.

Introduction

Photochirogenesis, an area of research largely influenced by many seminal contributions of Y. Inoue *et al.*,[1] rests on the transmission of chiral information from an external source to a prochiral photochemical substrate. When considering template-induced enantioselectivity in photochemical reactions,[2] the use and application of hydrogen bond-forming complexing agents has become a field of growing interest.[3] Research in our group has led to the development of the chiral template **1** (Fig. 1),[4,5] which is available in both enantiomeric forms and which has been established as a superior reagent to induce enantioselectivity in photochemical[6] and radical[7] reactions.

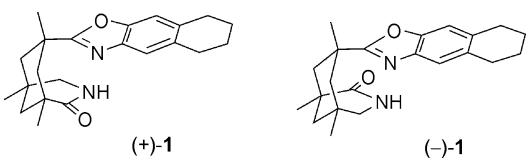

Fig. 1 Chiral templates (+)-**1** and (–)-**1** with a lactam as motif for hydrogen bonding.

Despite the high enantioselectivities, which can be achieved with template **1**, its use suffers from the fact that superstoichiometric amounts (mostly 2.5 equiv.) are required to achieve a high asymmetric induction. Indeed, the association properties of the substrate and the product do not differ significantly. Consequently, the product competes with the substrate for binding to the template. Only in cases in which product association is significantly disfavoured, the stoichiometric use of template **1** can lead to high enantioselectivities. A case in point is the photoinduced [4 + 2]-cycloaddition of 1,2,3,4-tetrahydro-2-oxoquinoline-5-aldehyde.[8] The compound exhibits a dihydroquinolone binding site and forms bulky cycloaddition products with alkenes. Their association to the template is low and it was shown that the enantioselectivity of the photochemical reaction increases when the reaction proceeds.[8b] While in this instance the steric demand of the product is responsible for the diminished product association, one could imagine a scenario in which the binding motif disappears in the reaction course. In other words, the substrate shows a two-point hydrogen bonding motif capable of binding to lactam **1**, whereas the photochemical reaction product does not show this motif any more. When searching for possible reactions of this type, we came across the formal [3 + 2]-photocycloaddition reactions of 2-hydroxy- (**2a**) and 2-amino-1,4-naphthoquinone (**2b**)[9] with olefins (Scheme 1), which was discovered and closely investigated by Suginome *et al.*[10]

As illustrated by the reaction with isobutene, naphthoquinone-anellated dihydrofurans and dihydropyrroles **5** are formed. One hydrogen binding site completely vanishes in the case of substrate **2a** or is significantly disturbed in the case of substrate **2b**. Mechanistically, the reaction can be explained by addition of isobutene to the photoexcited substrate resulting in 1,4-biradical **3**, which undergoes a tautomerisation-induced spin-centre shift[11] to 1,5-biradical **4**. The reaction is completed by carbon-heteroatom

Lehrstuhl für sOrganische Chemie I, Technische Universität München, Lichtenbergstr. 4, 85747, Garching, Germany. E-mail: thorsten.bach@ch.tum.de; Fax: +49 89 13315; Tel: +49 89 13330

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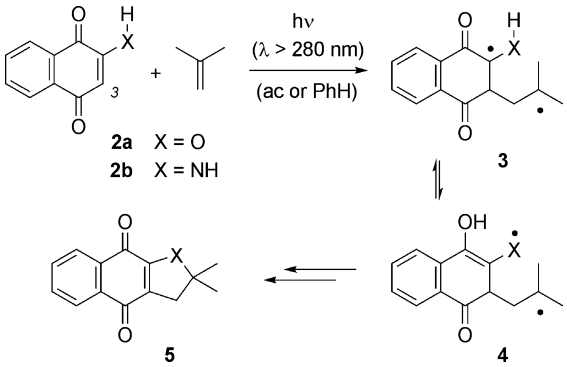
‡ Electronic supplementary information (ESI) available: Details on the calculation of association constants. See DOI: 10.1039/c1pp05049d

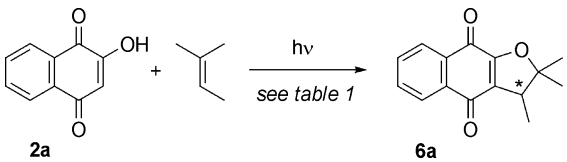


Scheme 1 Simplified mechanistic course of the formal [3 + 2]-photocycloaddition of 2-hydroxy- (**2a**) and 2-amino-1,4-naphthoquinone (**2b**) with isobutene as described by Suginome *et al.*[10]

bond formation to a hydroquinone intermediate, which is further oxidised to product **5**. Other intermediates have been invoked and further mechanistic details can be found in the literature.[10] Apparently, there is no stereogenic centre formed with isobutene. However, one can imagine that cyclic alkenes could be favourably used in this reaction. In this paper, we disclose the results of a study which aimed at reactions of substrates **2** with cyclic alkenes and in which we addressed the question of enantioselective bond formation in these reactions.

Results and discussion

The original conditions used by Suginome *et al.* to achieve the formal [3 + 2]-photocycloaddition of the title compounds included irradiation in benzene or acetone with a 500 W high pressure mercury lamp (Pyrex vessel) employing an excess of the olefin at ambient temperature. The conditions needed some adjustment as the template **1** is favourably used in a non-polar solvent at low temperature and as irradiation is best performed at a specific wavelength region avoiding unnecessary heat evolution. In order to find optimum conditions the known reaction of 2-hydroxy-1,4-naphthoquinone (**2a**) and 2-methyl-2-butene (Scheme 2) was studied.



Scheme 2 Optimisation of the [3 + 2]-photocycloaddition between 2-hydroxy-1,4-naphthoquinone (**2a**) and 2-methyl-2-butene.

Initial experiments were conducted in a Rayonet RPR-100 reactor with 16 lamps as external light sources at ambient temperature.[12] The reaction with 20 equivalents of the alkene in benzene as the solvent at λ = 300 nm resulted in the formation of 43% of the desired product **6a**[10b] (Table 1, entry 1). The yield was lower than reported in the literature (77% in benzene, 65% in acetone) employing the above-mentioned conditions. Changing the solvent (entries 2–4) only led to a significant improvement if acetone was employed (entry 4). In this instance the yield was high and the conversion was complete after three hours indicating

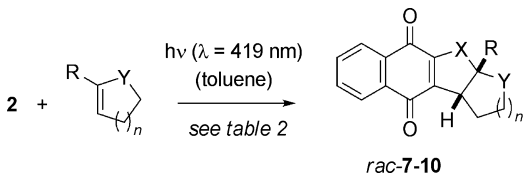
Table 1 Yield of photocycloaddition product **6a** (see Scheme 2) depending on the irradiation conditions

Entry	Solvent	*t* [h]	Equiv.[a]	λ [nm]	Yield [%][b]
1	benzene	6	20	300[c]	43
2	toluene	7	20	300[c]	38
3	acetonitrile	5	20	300[c]	45
4	acetone	3	20	300[c]	74
5	toluene	4.5	200	300[c]	42
6	toluene	4.5	200	350[d]	49
7	toluene	4.5	200	419[e]	68

[a] Equivalents of 2-methyl-2-butene. [b] Yield of isolated product. [c] Rayonet RPR-3000 Å [d] Rayonet RPR-3500 Å. [e] Rayonet RPR-4190 Å.

a significant triplet sensitisation by the solvent. Due to its polarity, acetone is not suitable for experiments with the hydrogen-bonding template **1**. Further optimisation studies were therefore conducted in toluene as the solvent despite the fact that the reaction was not complete in this solvent after seven hours (72% conversion) and led only to a yield of 38%. While a further increase of the 2-methyl-2-butene concentration (entry 5) was not particularly successful, except for the fact that the reaction went to completion after 4.5 h, the adaptation of the irradiation wavelength to the absorption properties of the substrate turned out to be more rewarding (entries 6, 7). Theoretical studies predict for 2-hydroxy-1,4-naphthoquinone (**2a**) a long wavelength absorption due to two n → π* electronic transitions (at 400–500 nm).[13] Despite the fact that these absorptions are weak in nonpolar solvents, excitation at λ = 419 nm in toluene turned out to bring about a rapid and clean photocycloaddition providing the desired product in 68% yield (entry 7). Preliminary experiments with other alkenes showed a similar trend as observed for 2-methyl-2-butene.

As a result of the optimisation experiments, further reactions of substrates **2** were conducted at a substrate concentration of 10 mM in toluene as the solvent at λ = 419 nm using 200 equivalents of the respective alkene (Scheme 3). Cyclic alkenes were chosen as substrates because it was expected that they would lead to a single diastereomeric product, in which the two substituents at the former double bond would be *cis*-oriented.



Scheme 3 [3 + 2]-photocycloaddition of 2-hydroxy- (**2a**) and 2-amino-1,4-naphthoquinone (**2b**) with cyclic olefins to the racemic products *rac*-**7**–**10**.

Under optimised conditions various cyclic alkenes were shown to react with naphthoquinones **2a** and **2b** in moderate to very good yields (Table 2). All products, except for products *rac*-**7**[10b,c] derived from cyclopentene, have not been previously described.

There is no immediate correlation between chemical structure and yield. Cyclopentene gave better results in the reaction with substrate **2a** as compared to cyclohexene (entries 1, 2). With substrate **2b** the situation was reversed (entries 5, 6) and the yield for *rac*-**8b** was higher than for *rac*-**7b**. The more electron-rich dihydropyran (entry 4) gave a similar yield in its reaction with **2a**

Table 2 Yield of photocycloaddition products *rac*-**7–10** (see Scheme 3) for different starting materials

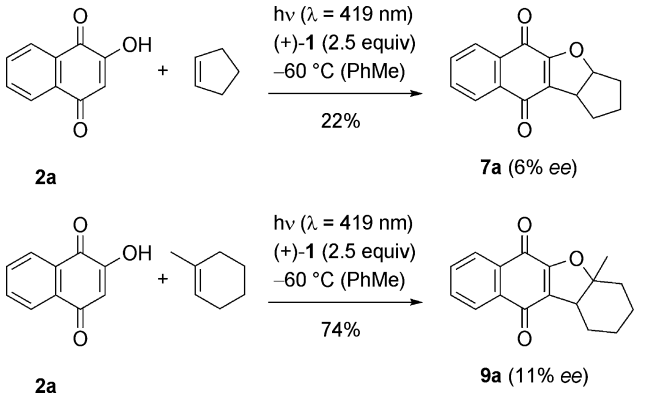
Entry[a]	Substrate	X	Y	*R*	*n*	Product	Yield [%][b]
1	**2a**	O	CH_2	H	1	*rac*-**7a**	44
2	**2a**	O	CH_2	H	2	*rac*-**8a**	33
3	**2a**	O	CH_2	Me	2	*rac*-**9a**	81
4	**2a**	O	O	H	2	*rac*-**10a**	47
5	**2b**	NH	CH_2	H	1	*rac*-**7b**	23
6	**2b**	NH	CH_2	H	2	*rac*-**8b**[c]	35
7	**2b**	NH	CH_2	Me	2	*rac*-**9b**	66

[a] The reactions were performed in toluene as the solvent at ambient temperature and at a substrate concentration of c = 10 mM employing the olefin in excess (200 equiv.). [b] Yield of isolated product. [c] The product was not isolated in pure form and could not be fully characterised.

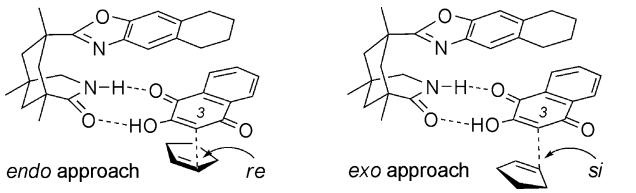
as did cyclopentene (entry 1). The only olefin that showed clearly superior behaviour was 1-methylcyclohex-1-ene, which with both naphthoquinones provided the respective products *rac*-**9** in good to very good yields. The *cis*-configuration of the products *rac*-**9–10** was confirmed by NOE studies, which revealed a strong spatial proximity of the substituent R (H or Me) and the hydrogen atom H (Scheme 3). Side products, which could be identified either in the crude product mixture or after product separation, included the C-3 connected dimer of the respective 1,4-naphthoquinone and the non-oxidized hydroquinone precursor of products *rac*-**7–10**.

Enantioselective reactions were performed in toluene at –60 °C employing (+)-**1** as the chiral template. Disappointingly, the observed selectivities were relatively low. Employing an array of alkenes, both cyclic and acyclic, there was no enantioselectivity detected in the [3 + 2]-photocycloaddition of 2-amino-1,4-naphthoquinone (**2b**). The experiments with 2-hydroxy-1,4-naphthoquinone (**2a**) were slightly more successful (Scheme 4). While there was no enantioselectivity in the reaction with 2-methyl-2-butene (to product **6a**), the reactions with the cyclic alkenes cyclopentene and 1-methylcyclohex-1-ene did deliver chiral products with a detectable enantiomeric excess (*ee*). The former olefin gave the expected product **7a** with 6% *ee*, the latter olefin gave product **9a** with 11% *ee* and in a good yield of 74%.

Although the relatively low selectivities appear to indicate that the concept presented in the introduction had failed, there are two major issues to be considered when analyzing the enantioselectivity of the reaction. First, the photocycloaddition under scrutiny is a reaction in which – contrary to all reactions yet studied with template **1** – the stereogenic centre in the final product does not evolve from the substrate, which is bound to the template. Rather the approach of the olefin to the template is decisive for the outcome. In other words, the reaction may be perfectly enantioselective regarding a C–C bond formation at C3 of the 2-substituted naphthoquinone, but the relative configuration of the two stereogenic centres, between which the bond is formed, determines the absolute configuration in the product. As illustrated in Scheme 5 for the approach of cyclopentene to photoexcited substrate **2a** bound to template (+)-**1**, only a clean *exo* or *endo* approach of the olefin secures a high asymmetric induction to be preserved in the product. Due to tautomerisation and further oxidation of the former naphthoquinone carbon atom C-3 the information about the direct induction of the template vanishes.



Scheme 4 Enantioselective [3 + 2]-photocycloaddition reactions of 2-hydroxy-1,4-naphthoquinone (**2a**) and cyclic alkenes.



Scheme 5 Absolute configuration of product **7a** depending on the approach of the olefin substrate (*re vs. si* face attack).

A second aspect to be considered concerns the association equilibrium. The binding of substrate **2a** to template (+)-**1** as well as a possible dimerisation of substrate **2a** were studied by NMR titration experiments.[14] It was shown earlier that there is – for steric reasons – no homochiral dimerisation of (+)-**1**.[6c] The dimerisation behaviour of the substrate was studied in a dilution experiment[14a] in which samples of **2a** dissolved in toluene-d_8 were prepared with concentrations from 70 mmol L^{-1} down to 500 µmol L^{-1}. Within this range a more or less linear change in chemical shift of less than 0.01 ppm was detected indicating that a dimerisation of the substrate is of no relevance for this investigation (K_{dim} < 50 L mol^{-1}). The association of substrate **2a** to the template was studied in a titration experiment in which the substrate concentration was varied from 2.7 mmol L^{-1} to 59 mmol L^{-1} at a constant template concentration of 28 mmol L^{-1}. The quantitative evaluation of the data obtained in this experiment using HOSTEST[15] showed that an interpretation on the basis of the anticipated 1 : 1 complex stoichiometry was not possible. Only if a substrate : template stoichiometry of 2 : 1 was taken into account, the measured data were in good accordance with the predicted values. Based on this assumption two binding constants can be tentatively assigned, a small binding constant for the 1 : 1 complex ($K_{a,1:1}$ ≈ 100 L mol^{-1}) and a large binding constant for the 1 : 2 complex ($K_{a,2:1}$ ≈ 2000 L mol^{-1}).[16] These findings raise questions about the possible structure of the ternary complex and the consequences for the enantioselectivity in this reaction. Preliminary theoretical studies using a semi-empirical method (PM6,[17] Gaussian09) revealed that both matched (both substrate molecules preferentially expose the same side) and mismatched cases are conceivable. If tautomeric structures of the substrate are taken into account the analysis gets even more complicated. Given the number of possible structures with similar energies, no further attempts were made to identify a single 2 : 1 complex structure.

Conclusions

In summary, the formal [3 + 2]-photocycloaddition of cyclic alkenes to naphthoquinones **2** turned out to be a useful reaction to photochemically access new tetracyclic scaffolds. While the reaction was high yielding (up to 81% yield) and diastereoselective for some substrate-alkene combinations, it failed to deliver enantiomerically pure products when conducted in the presence of chiral template (+)-**1**. One reason for the observed low enantioselectivity could be an unselective approach of the cyclic olefin to the photoexcited substrate. Another reason to be considered is the fact that no defined complex formation could be detected but rather mixtures of 1 : 1 and 2 : 1 substrate-template complexes are likely to be present under the reaction conditions. Despite the limited success encountered with naphthoquinones further studies in our lab continue to devise photochemical reactions of hydrogen bonding substrates, in which the binding site vanishes in the course of the reaction.

Experimental

General methods

Chemicals were either commercially available or prepared according to the cited references. TLC was performed on silica coated glass plates (silica gel 60 F_{254}) with detection by UV (254 nm). Flash chromatography was performed on silica gel 60 (Merck, 230–400 mesh) with pentane–ethyl acetate (P/EtOAc) as eluent. HPLC analyses for the determination of the enantiomeric ratio of compounds **7a** and **9a** were performed on Chiralpak AD-RH (Daicel, 250 × 4.6 mm, 5 µm) employing acetonitrile–water (MeCN–H_2O) as eluent and UV-detection at 20 °C. IR: JASCO IR-4100 (ATR) or Perkin–Elmer 1600 FT/IR. MS/HRMS: Finnigan MAT 8200 (EI)/Finnigan MAT 95S (HR-EI). ^{1}H and ^{13}C NMR: Bruker AV-360, recorded at 303 K; chemical shifts are reported relative to tetramethylsilane. The multiplicities of the ^{13}C NMR signal were determined by DEPT experiments. Assignments are based on COSY and HMQC experiments. Diastereotopic protons (′) and interconvertible assignments (* or #) are labelled. Irradiations were performed in a Rayonet RPR-100 reactor (Southern New England Ultra Violet Company, Connecticut, USA) using RPR-4190 Å fluorescent lamps.[12] 2-Amino-1,4-naphthoquinone (**2b**) was synthesised from 1,4-naphthoquinone and *O*-benzylhydroxylamine following a literature procedure.[9]

General procedure for the irradiation at ambient temperature

The photocycloaddition precursors where dissolved in a flame-dried Duran irradiation tube under argon in degassed dry solvent. After addition of the alkene (10–200 eq.) the mixture was irradiated at 419 nm (RPR-4190 Å) until full conversion could be detected by TLC. After removal of the solvent and the excess alkene *in vacuo* the crude product was purified by flash column chromatography.

1-*H*-2,3,3a,10b-Tetrahydro-cyclopenta[b]naphtho[2,3-d]furan-5,10-dione (*rac*-7a). According to the general procedure, 18.0 mg (103 µmol) of 2-hydroxy-1,4-naphthoquinone (**2a**) and 1.76 mL (1.36 g, 20.0 mmol) cyclopentene dissolved in 10 mL toluene were irradiated for 4.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 7/1) delivered 10.9 mg (45.3 µmol, 44%) of compound *rac*-**7a** as a yellow solid. mp: 124 °C; TLC: R_f 0.24 (P/EtOAc 7/1) [UV]; ^{1}H-NMR (360 MHz, $CDCl_3$): δ (ppm) = 1.53–1.59 (m, 1 H, H-2), 1.77–1.94 (m, 3 H, H-2′, H-3, H-1), 2.00–2.10 (m, 1 H, H-1′), 2.22–2.31 (m, 1 H, H-3′), 3.94 (*virt.* dt, ^3J = 8.4 Hz, ^3J = 1.8 Hz, 1 H, H-10b), 5.45 (dd, ^3J = 8.4 Hz, ^3J = 5.4 Hz, 1 H, H-3a), 7.65–7.72 (m, 2 H, H-7, H-8), 8.04–8.07 (m, 2 H, H-6, H-9). ^{13}C-NMR (90.6 MHz, $CDCl_3$): δ (ppm) = 23.4 (t, C-2), 31.8 (t, C-1), 35.0 (t, C-3), 45.1 (d, C-10b), 92.5 (s, C-3a), 126.0 (d, C-6*), 126.2 (d, C-9*), 130.8 (s, C-10a), 131.6 (s, C-5a*), 132.7 (d, C-7#), 133.3 (s, C-9a*), 134.0 (d, C-8#), 160.2 (s, C-4a), 177.9 (s, C-5), 182.2 (s, C-10). The analytical data for compound *rac*-**7a** were in agreement with the literature data.[10b]

1,2,3,4,4a,11b-Hexahydro-benzo[b]naphtho[2,3-d]-furan-6,11-dione (*rac*-8a). According to the general procedure, 18.0 mg (103 µmol) of 2-hydroxy-1,4-naphthoquinone (**2a**) and 2.03 mL (1.64 g, 20.0 mmol) cyclohexene dissolved in 10 mL toluene were irradiated for 4.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 7/1) delivered 8.60 mg (33.8 µmol, 33%) of compound *rac*-**8a** as a yellow solid. mp: 103 °C; TLC: R_f 0.26 (P/EtOAc 7/1) [UV]; IR (KBr): $\tilde{\nu}$ = 2930 cm^{-1} (s, CH), 2857 (m, CH), 1766 (w), 1681 (s, CO), 1649 (m, C═C), 1611 (m, C═C), 1592 (s, C═C), 1448 (m, CH), 1398 (w), 1367 (m), 1255 (s), 1217 (m), 1195 (s), 1160 (w), 1113 (w, COCH), 984 (m), 949 (m), 900 (w, CH_{ar}), 857 (w, CH_{ar}), 792 (w, CH_{ar}), 717 (m, CH_{ar}).; ^{1}H-NMR (360 MHz, $CDCl_3$): δ (ppm) = 1.38–1.58 (m, 4 H, H-2, H-2′, H-3, H-3′), 1.79–1.93 (m, 2 H, H-1, H-4′), 2.06–2.16 (m, 1 H, H-1′), 2.22–2.32 (m, 1 H, H-4′), 3.36 (ddd, ^3J = 6.5 Hz, ^3J = 8.5 Hz, ^3J = 8.7 Hz, 1 H, H-11b), 4.88 (*virt.* dt, ^3J = 4.1 Hz, ^3J = 8.5 Hz, 1 H, H-4a), 7.66–7.71 (m, 2 H, H-8, H-9), 8.05–8.09 (m, 2 H, H-7, H-10). ^{13}C-NMR (90.6 MHz, $CDCl_3$): δ (ppm) = 19.6 (t, C-2*), 21.4 (t, C-3*), 26.5 (t, C-1), 27.1 (t, C-4), 39.2 (d, C-11b), 86.2 (s, C-11a), 126.0 (d, C-7*), 126.2 (d, C-10*), 130.2 (d, C-4a), 131.5 (s, C-6a*), 132.9 (d, C-8#), 133.2 (s, C-10a*), 134.1 (d, C-9#), 160.6 (s, C-5a), 178.9 (s, C-6), 182.7 (s, C-11). MS (EI, 70 eV), *m/z* (%): 254 (88) [M^+], 188 (54) [M^+-C_5H_6], 176 (49) [M^+-C_6H_6], 147 (100) [M^+-C_7H_7O], 105 (28), 77 (25) [$C_6H_5^+$]; HRMS (EI) ($C_{16}H_{14}O_3$): required: 254.0943, found: 254.0938.

4a-Methyl-1,2,3,4,11b-pentahydro-benzo[b]naphtho[2,3-d]furan-6,11-dione (*rac*-9a). According to the general procedure, 18.0 mg (103 µmol) of 2-hydroxy-1,4-naphthoquinone (**2a**) and 2.37 mL (1.92 g, 20.0 mmol) 1-methylcyclohex-1-ene dissolved in 10 mL toluene were irradiated for 4.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 3/1) delivered 22.5 mg (83.9 µmol, 81%) of compound *rac*-**9a** as a yellow solid. mp: 71 °C; TLC: R_f 0.67 (P/EtOAc 3/1); IR (KBr): $\tilde{\nu}$ = 2933 cm^{-1} (s, CH), 2861 (m, CH), 1679 (s, CO), 1646 (s, C═C), 1617 (s, C═C), 1593 (s, C═C), 1572 (m), 1447 (m, CH), 1390 (m), 1365 (m), 1312 (w), 1259 (m), 1208 (m), 1183 (m), 1038 (m), 954 (m, COCH), 907 (w, CH_{ar}), 878 (w, CH_{ar}), 841 (w, CH_{ar}), 794 (m, CH_{ar}, CH), 721 (m, CH_{ar}), 680 (s, CH_{ar}); ^{1}H-NMR (360 MHz, $CDCl_3$): δ (ppm) = 1.40–1.54 (m, 6 H, H-2*, H-2′*, H-3*, H-12), 1.70–1.80 (m, 2 H, H-3′*, H-4), 1.83–1.95 (m, 2 H, H-1, H-1′), 2.00–2.10 (m, 1 H, H-4′), 3.19 (*virt.* t, ^3J = 6.1 Hz, 1 H, H-11b), 7.63–7.72 (m, 2 H, H-8, H-9), 8.03–8.08 (m, 2 H, H-7, H-10); ^{13}C-NMR (90.6 MHz, $CDCl_3$): δ (ppm) = 18.9 (t, C-2*), 19.3 (t, C-3*), 24.8 (t, C-1), 27.0 (q, C-12), 32.2 (t, C-4), 45.4 (d, C-11b), 93.1 (s, C-11a), 125.9 (d, C-7*), 126.2 (d, C-10*), 127.6 (s, C-4a), 131.6 (s, C-6a*), 132.8

(d, C-8#), 133.3 (s, C-10a*), 134.0 (d, C-9#), 159.2 (s, C-5a), 178.7 (s, C-6), 182.7 (s, C-11); MS (EI, 70 eV), *m/z* (%):268 (100) [M^+], 253 (43) [M^+-CH_3], 188 (51) [M^+-C_6H_8], 147 (19) [M^+-C_8H_9O], 95 (38), 43 (52) [$C_3H_7^+$]. HRMS (EI) ($C_{17}H_{16}O_3$): required: 268.1100, found: 268.1097.

2-*H*-3,4,4a,11a-Tetrahydro-naphtho[2,3-b]pyrano[5,6-d]furan-5,10-dione (*rac*-10a). According to the general procedure, 18.0 mg (103 µmol) of 2-hydroxy-1,4-naphthoquinone (**2a**) and 1.82 mL (1.68 g, 20.0 mmol) 3,4-dihydro-2*H*-pyran dissolved in 10 mL toluene were irradiated for 4.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 3/1) delivered 12.4 mg (48.4 µmol, 47%) of compound *rac*-**10a** as a yellow solid. mp: 166 °C; TLC: R_f 0.21 (P/EtOAc 6/1); IR (KBr): $\tilde{\nu}$ = 2929 cm^{-1} (m, CH), 2868 (m, CH), 1678 (s, CO), 1677 (s, C═C), 1644 (s, C═C), 1591 (s, C═C), 1572 (m), 1452 (m, CH), 1387 (m), 1361 (m), 1248 (m), 1219 (m), 1192 (s), 1155 (s), 1119 (s, COCH), 1066 (m), 1036 (s), 982 (m), 941 (s), 908 (s, CH_{ar}), 860 (w, CH_{ar}), 808 (s, CH_{ar}), 758 (m, CH_{ar}, CH), 717 (vs, CH_{ar}), 692 (s, CH_{ar}). ^{1}H-NMR (360 MHz, $CDCl_3$): δ (ppm) = 1.60–1.83 (m, 2 H, H-3, H-3′), 1.88–1.98 (m, 1 H, H-4), 2.08–2.19 (m, 1 H, H-4′), 3.45 (*virt.* dt, ^3J = 7.5 Hz, ^3J = 6.3 Hz, 1 H, H-4a), 3.83–3.95 (m, 2 H, H-2, H-2′), 6.18 (d, ^3J = 7.5 Hz, 1 H, H-11a), 7.67–7.75 (m, 2 H, H-7, H-8), 8.05–8.11 (m, 2 H, H-6, H-9); ^{13}C-NMR (90.6 MHz, $CDCl_3$): δ (ppm) = 19.4 (t, C-3), 20.9 (t, C-4), 36.6 (d, C-4a), 60.9 (t, C-2), 107.6 (s, C-11a), 126.0 (d, C-6*), 126.3 (d, C-9*), 126.8 (d, C-4b), 131.4 (s, C-5a*), 132.9 (s, C-9a*), 133.1 (d, C-7*), 134.1 (d, C-8*), 158.9 (s, C-10a), 177.5 (s, C-10*), 181.9 (s, C-5*); MS (EI, 70 eV), *m/z* (%): 256 (72) [M^+], 228 (33) [M^+-C_2H_2], 173 (70) [M^+-C_5H_5O], 115 (18) [M^+-$C_8H_8O_2$], 84 (100) [M^+-C_7H_7O], 55 (27) [$C_4H_7^+$]. HRMS (EI) ($C_{15}H_{12}O_4$): required: 256.0736, found: 256.0734.

1-*H*-2,3,3a,10b-Tetrahydro-cyclopenta[b]naphtho[2,3-d]pyrrol-5,10-dione (*rac*-7b). According to the general procedure, 20.0 mg (115 µmol) of 2-amino-1,4-naphthoquinone (**2b**) and 2.12 mL (1.63 g, 24.0 mmol) cyclopentene dissolved in 25 mL toluene were irradiated for 4.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 3/1) delivered 6.30 mg (26.3 µmol, 23%) of compound *rac*-**7b** as a red solid. mp: 229 °C; TLC: R_f 0.27 (P/EtOAc 3/1) [UV]; ^{1}H-NMR (360 MHz, $CDCl_3$): δ (ppm) = 1.49–1.57 (m, 1 H, H-2), 1.68–1.77 (m, 1 H, H-2′), 1.78–1.90 (m, 2 H, H-3, H-3′), 1.90–2.04 (m, 2 H, H-1, H-1′), 3.92–4.00 (m, 1 H, H-10b), 4.49–4.58 (m, 1 H, H-3a), 5.21 (s, 1 H, NH), 7.55 (*virt.* dt, ^3J = 7.6 Hz, ^4J = 1.3 Hz, 1 H, H-6*), 7.67 (*virt.* dt, ^3J = 7.6 Hz, ^4J = 1.4 Hz, 1 H, H-9*), 7.95 (dd, ^3J = 7.6 Hz, ^4J = 1.4 Hz, 1 H, H-7#), 8.06 (dd, ^3J = 7.6 Hz, ^4J = 1.3 Hz, 1 H, H-8#); ^{13}C-NMR (90.6 MHz, $CDCl_3$): δ (ppm) = 24.3 (t, C-2), 32.8 (t, C-1), 36.5 (t, C-3), 45.9 (d, C-10b), 63.8 (d, C-3a), 120.3 (s, C-10a), 125.4 (d, C-6*), 125.6 (d, C-9*), 131.2 (d, C-8#), 131.5 (s, C-5a*), 134.2 (d, C-7#), 134.8 (s, C-9a*), 152.3 (s, C-4a), 179.8 (s, C-5), 179.9 (s, C-10). The analytical data for compound *rac*-**7b** were in agreement with the literature data.[10c]

4a-Methyl-1,2,3,4,4a,11b-hexahydro-naphtho[2,3-b]indole-6,11-dione (*rac*-9b). According to the general procedure, 20.0 mg (115 µmol) of 2-amino-1,4-naphthoquinone (**2b**) and 2.73 mL (2.21 g, 23.0 mmol) 1-methylcyclohex-1-ene dissolved in 25 mL toluene were irradiated for 4.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 3/1) delivered 20.3 mg (75.9 µmol, 66%) of compound *rac*-**9b** as a red solid. mp: 176 °C; TLC: R_f 0.56 (P/EtOAc 3/1); IR (KBr): $\tilde{\nu}$ = 3335 cm^{-1} (m, NH), 3056 (w), 2928 (s, CH), 2855 (m, CH), 1769 (m, CO), 1671 (s, C═C), 1616 (m, CH_{ar}), 1590 (s, CH_{ar}), 1563 (s, CH_{ar}), 1482 (s), 1445 (s), 1383 (m), 1352 (m), 1298 (w), 1270 (w), 1261 (w), 1217 (m), 1127 (w), 1013 (w), 945 (w, CH_{ar}), 853 (w, CH_{ar}), 791 (w, CH_{ar}), 724 (m, CH_{ar}), 698 (w, CH_{ar}); ^{1}H-NMR (360 MHz, $CDCl_3$): δ (ppm) = 1.30 (s, 3 H, H-12), 1.42–1.69 (m, 5 H, H-2, H-2′, H-3, H-3′, H-4), 1.69–1.83 (m, 2 H, H-1, H-4′), 1.88–2.00 (m, 1 H, H-1′), 3.02 (dt, ^3J = 7.2 Hz, ^3J = 6.3 Hz, 1 H, H-11b), 4.95 (s, 1 H, NH), 7.56 (*virt.* dt ^3J = 7.6 Hz, ^4J = 1.4 Hz, 1 H, H-7*), 7.67 (*virt.* dt ^3J = 7.6 Hz, ^4J = 1.4 Hz, 1 H, H-10*), 7.96 (dd ^3J = 7.6 Hz, ^4J = 1.4 Hz, ^5J = 0.5 Hz, 1 H, H-8*), 8.05 (dd ^3J = 7.6 Hz, ^4J = 1.4 Hz, ^5J = 0.5 Hz, 1 H, H-9*); ^{13}C-NMR (90.6 MHz, $CDCl_3$): δ (ppm) = 20.7 (t, C-2*), 21.2 (t, C-3*), 25.9 (t, C-1), 27.8 (q, C-12), 34.2 (t, C-4), 46.3 (d, C-11b), 64.2 (s, C-4a), 122.3 (s, C-11a), 125.4 (d, C-8*), 125.6 (d, C-9*), 131.5 (s, C-10a#) 131.6 (d, C-7*), 134.1 (d, C-10*), 134.7 (s, C-6#), 151.2 (s, C-5a), 180.5 (s, C-6), 180.6 (s, C-11); MS (EI, 70 eV), *m/z* (%): 267 (9) [M^+], 252 (8) [M^+-CH_3], 223 (9) [M^+-C_3H_8], 176 (100), 147 (9) [M^+-$C_8H_{10}N$], 95 (22), 55 (11), 41 (7) [$C_3H_5^+$]. HRMS (EI) ($C_{17}H_{17}NO_2$): required: 267.1259, found: 267.1258.

General procedure for attempted enantioselective photocycloaddition reactions at low temperature

The photocycloaddition precursors and 2.5 eq. of the chiral template (+)-**1** were dissolved in a flame dried Durane irradiation tube under argon in degassed dry solvent. After addition of the alkene (10–200 eq.) the mixture was cooled to –60 °C under argon pressure and was irradiated at 419 nm until full conversion could be detected by TLC. After removal of the solvent and the excess alkene *in vacuo* the crude product was purified by flash column chromatography.

1,2,3,3a,4,10b-Hexahydro-naphtho[2,3-b]cyclopenta[d]furan-5,10-dione (7a). According to the general procedure, 18.0 mg (103 µmol) of 2-hydroxy-1,4-naphthoquinone (**2a**), 91.0 mg (258 µmol) template (+)-**1** and 1.76 mL (1.36 g, 20.0 mmol) cyclopentene dissolved in 15 mL toluene were irradiated for 6.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 7/1) delivered 5.2 mg (21.6 µmol, 22%) of compound **7a** (6% *ee*) as a yellow solid. HPLC (AD-RH, MeCN–H_2O 50/50, detection at λ = 300 nm): t_R = 11.19 min, t_R = 13.58 min.

4a-Methyl-1,2,3,4,11b-pentahydro-naphtho[2,3-b]benzo[d]furan-6,11-dione (9a). According to the general procedure, 18.0 mg (103 µmol) of 2-hydroxy-1,4-naphthoquinone (**2a**), 91.0 mg (258 µmol) template (+)-**1** and 2.37 mL (1.92 g, 20.0 mmol) 1-methyl-1-cyclohexene dissolved in 20 mL toluene were irradiated for 6.5 h. Purification by flash column chromatography (2 g SiO_2, P/EtOAc 3/1) delivered 20.4 mg (76.0 µmol, 74%) of compound **9a** (11% *ee*) as a yellow solid. HPLC (AD-RH, MeCN–H_2O 70/30, detection at λ = 250 nm): t_R = 10.56 min, t_R = 13.85 min.

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