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Synthesis and structural study of [2.*n*](2,5)pyridinophanes

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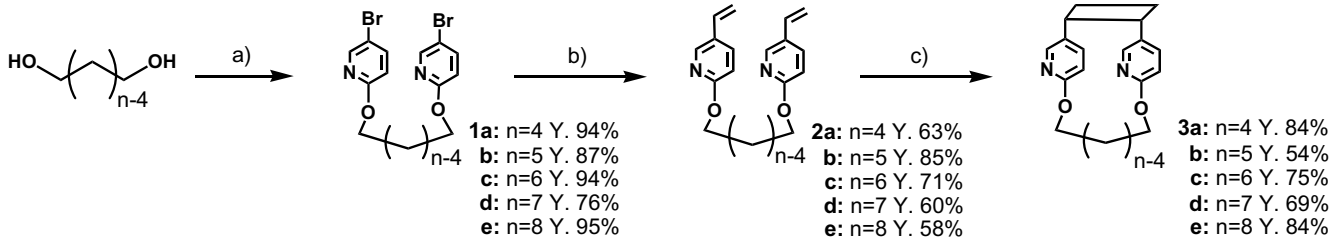
Abstract—[2.*n*](2,5)Pyridinophanes possessing a cyclobutane ring and dioxaoligomethylene chain as tethers were efficiently prepared by intramolecular [2 + 2] photocycloaddition of vinylpyridine derivatives using a 400-W high-pressure mercury lamp through a Pyrex filter. They were of *cis*-configuration with respect to the cyclobutane ring, which was proved by the specific methine proton signals at δ 3.95–4.14. If the dioxaoligomethylene chain is short, the reaction affords only two *exo*,*syn*- and *anti*-isomers among three possible ones. On the other hand, if the chain is long enough, it gives three possible isomers interconverting at equilibrium. It is concluded that [2.*n*](2,5)pyridinophanes are rigid if $n = 4$, 5 but flexible if $n \geqslant 6$.

Pyridinophanes are attracting much interest in structural organic chemistry, but so far only several have been prepared. For example, [2.2](2,5)pyridinophanes[1–3] were for the first time obtained by Hofmann-1,6-elimination of the corresponding ammonium hydroxide. Both [3.3](2,5)- and (2,6)pyridinophanes[4] were obtained and separated into several isomers. 1,4,11,14-Tetraoxa[4.4](2,6)pyridinophane was synthesized and its energy barrier (13.5 ± 0.3 kcal mol^{-1}) was reported for the interconversion among *syn*- and *anti*-isomers.[5] Nevertheless, the critical homologues for the interconvesion dynamics, [2.4]-, [2.5]-, and [2.6](2,5)pyridinophanes, have not yet been synthesized, although the question arises whether they can be isolated as isomers or exist as an interconverting isomer mixture at rt. Recently, we have found a facile photochemical synthesis by means of intramolecular [2 + 2] photocycloaddition using vinylpyridine derivatives, so that we were prompted to study a systematic synthesis of pyridinophanes possessing two pyridine rings, a cyclobutane ring, and dioxaoligomethylene tethers as well as the effect of the tether length on the dynamics of the interconversion between isomers.

From the corresponding dibromides **1**[6] precursor olefins **2**[7] were prepared by Stille reaction.[8] The photocycloaddition of **2** was carried out by using a 400-W high-pressure mercury lamp through a Pyrex filter. [2.*n*](2,5)Pyridinophanes ($n = 4$–8)[9] were easily obtained in quantitative to relatively high yields (Scheme 1).



Scheme 1. Preparation of [2.*n*](2,5)pyridinophanes. Reagents and conditions: (a) (1) NaH/THF, (2) 2,5-dibromopyridine/THF–DMF; (b) $CH_2 = CHSn(n\text{-}Bu)_3$, $Pd(PPh_3)_4$, 2,6-di-*tert*-butyl-4-methylphenol/toluene; (c) hν(>280 nm)/MeCN.

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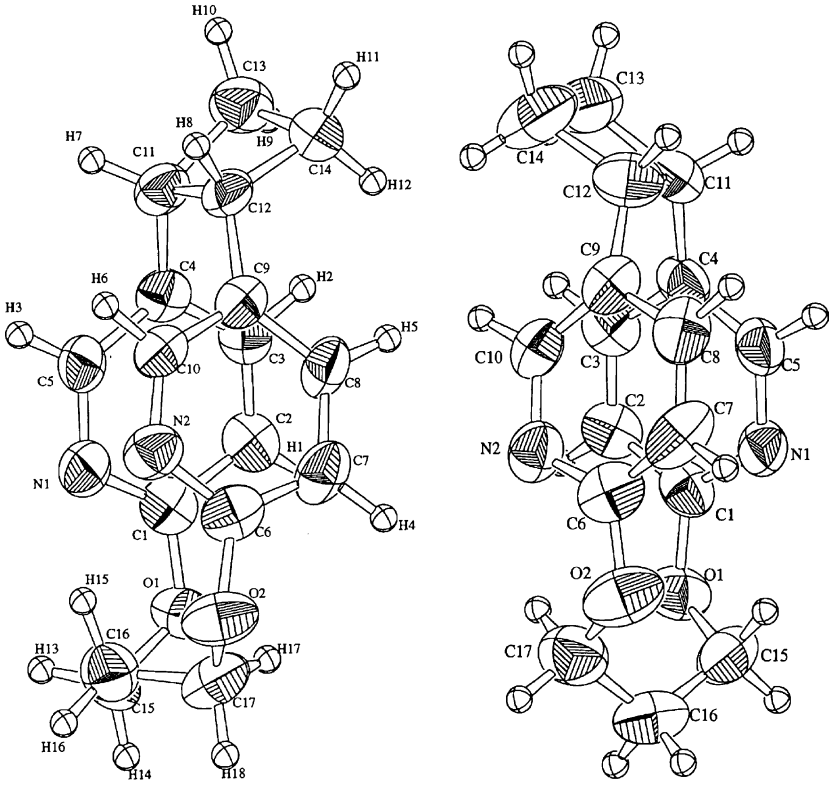


Figure 1. ORTEP drawings of **3b**(*exo*,*syn*) and **3b**(*anti*).

According to the ^{1}H NMR spectra taken by a JEOL Λ-500 FT NMR spectrometer, their aromatic proton peaks were high-field shifted compared with those of **2** (up to 0.72 ppm). They were also found to have *cis*-configuration at the cyclobutane ring, which was proved by the specific methine proton signals at δ 3.95–4.14 (in $CDCl_3$).[10]

The [2.4]- and [2.5](2,5)pyridinophanes **3a** and **b** were obtained as two isomers, *exo*,*syn*- and *anti*-ones in the ratio of 1:1 and 2:1, respectively. The isomers were separated and their structures were determined by X-ray crystallography as well as ^{1}H NMR spectroscopy.[9] The ORTEP drawings of **3b**(*exo*,*syn*) and (*anti*) are depicted in Figure 1.[11] C_s symmetric **3a**(*exo*,*syn*) and **b**(*exo*,*syn*) have only one set of proton peaks at the aromatic region, while C_1 symmetric **3a**(*anti*) and **b**(*anti*) have two sets of proton peaks at the region. Their isomers did not interconvert at rt for several months. Note that these reactions did not afford *endo*,*syn*-isomers **3a**(*endo*,*syn*) and **b**(*endo*,*syn*). The reason why the *endo*,*syn*-isomer did not form has not yet been rationalized. Further work on this complex photoreaction is now in progress and will be published elsewhere in the near future.

On the other hand, [2.*n*](2,5)pyridinophanes ($n \geqslant 6$) **3c**–**e** showed a single peak and a single spot in HPLC and TLC analyses, respectively, although many sets of pyridine protons of **3c** and **d** were detected by ^{1}H NMR experiments at 30 °C and those of **3e** were also observed at −105 °C, suggesting that they are of the equilibrium mixtures among *endo*,*syn*-, *exo*,*syn*-, and *anti*-isomers. The isomer ratio of **3c** is calculated to be 3:4:25 in the ^{1}H NMR spectrum taken at 30 °C. All aromatic protons broadened gradually with increasing temperature, but no clear coalescence temperature was observed up to 140 °C (upper limit of the solvent). As shown in Figure 2, **3d** shows broad peaks even at 30 °C. As the temperature was lowered, they become sharp. Using the spectrum at −90 °C, the ratio of *endo*,*syn*-, *exo*,*syn*-, and *anti*-isomers is calculated to be 2:3:6. These ratios of **3c** and **d** show the relative stabilities among the three isomers. In fact, the heat of formation (ΔH_f), determined at the PM3 level, decreases in the same order (see Table 1).

The coalescence temperature of **3d** was obtained at 61 °C. The temperature of **3e** was −84 °C, although its spectrum even at −105 °C was only partially resolved but not fully enough for the calculation of its isomer ratio. From these coalescence temperatures, the activation free energies of the interconversion are calculated and summarized in Table 2.[12] The ring rotation from *exo*,*syn*-isomer to *anti*-one suffers the steric interaction between aromatic C–H and cyclobutane CH_2, so that $\Delta G^{\ddagger}_{cX}$ is a little greater than $\Delta G^{\ddagger}_{cN}$.

Consequently, [2.*n*](2,5)pyridinophanes are conformationally rigid at the nuclei if their tether systems are equal to or smaller than those of [2.5]- and [3.3]-ones,[4] although they are flexible at the nuclei if the systems are equal to or larger than that of [2.6]-one. Structurally related paracyclophanes[13] and (1,4)naphthaleno-

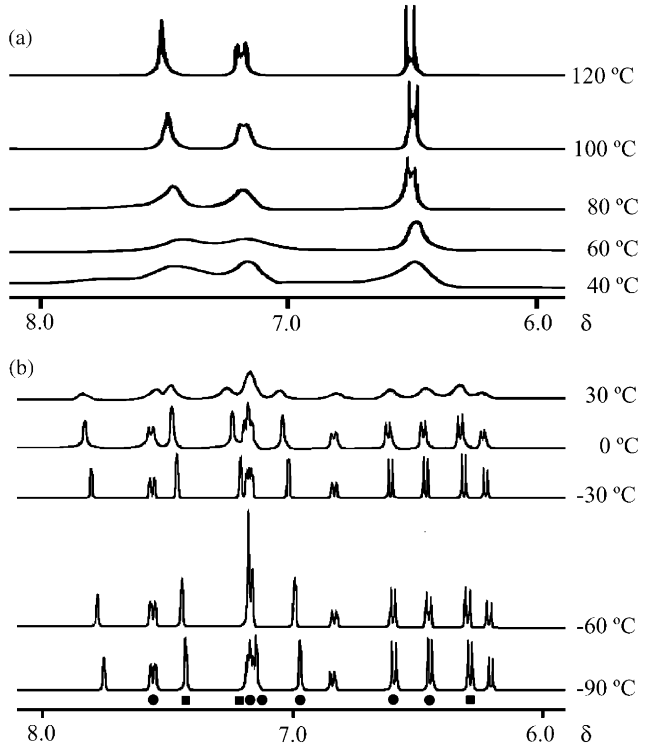
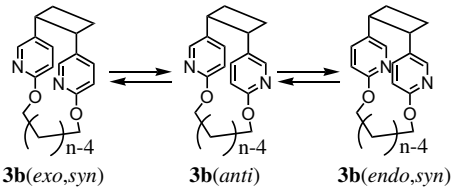


Figure 2. VT-NMR spectra of **3d**: (a) in 1,1,2,2-tetrachloroethane-d_2 and (b) CD_2Cl_2. The peaks due to *anti*- and *exo*,*syn*-isomers are marked by circles and squares, respectively. Unmarked peaks belong to the *endo*,*syn*-isomer.

Table 1. The heat of formation (ΔH_f, kcal mol^{-1}) of each isomer

Pyridinophane	*n*	*endo*,*syn*	*exo*,*syn*	*anti*
3c	6	−9.41	−9.82	−10.15
3d	7	−18.62	−18.95	−18.98

Table 2. Coalescence temperatures (T_c, °C) and activation free energies ($\Delta G_c^{\ddagger}$, kcal mol^{-1}) of **3**



3b(*exo*,*syn*) **3b**(*anti*) **3b**(*endo*,*syn*)

Compound	T_c	$\Delta\delta_N$[a,b]	$\Delta\delta_X$[a,c]	$\Delta G_{cN}^{\ddagger}$[b]	$\Delta G_{cX}^{\ddagger}$[c]
3c	>140[d]	391[e]	142[e]	>19	>20
3d	61[d]	423[f]	142[f]	15	16
3e	−84[g]	319[g,h]	144[g,h]	8[h]	9[h]

[a] Chemical shift difference.
[b] Between *endo*,*syn* and *anti*-isomers.
[c] Between *exo*,*syn* and *anti*-isomers.
[d] In 1,1,2,2-Tetrachloroethane-d_2.
[e] In $CDCl_3$.
[f] In CD_2Cl_2.
[g] In CD_2Cl_2–CS_2 (1/1, v/v).
[h] Estimated because of broad peaks.

phanes,[14] however, are rigid at the nuclei if the systems are equal to or smaller than that of [3.4]- and at least [2.7]-ones, respectively.[15] The pyridinophanes have smaller aromatic N atoms than aromatic C–H's and the ether linkages at the tethers, which undoubtedly is advantageous for the facile interconversion.

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6. Oligomethylene glycol (1.05×10^{-2} mol) was added to a suspension of NaH (60% in oil, 1.01 g, 2.52×10^{-2} mol, washed with hexane by decantation) in THF (10 mL). After the evolution of hydrogen gas ceased, a DMF (30 mL) solution of 2,5-dibromopyridine (10.00 g, 4.22×10^{-2} mol) was added to the suspension with stirring for 0.5 h at rt. Then the mixture was stirred for 2 h at 60 °C. After cooling to rt, to this reaction mixture was added 1:10 H_2O–THF solution to decompose excess NaH. The organic solution was poured into a separation funnel with 200 mL water. The aqueous solution was extracted with CH_2Cl_2 (200 mL×3) and then washed with water (200 mL×3). The organic layer was dried over $MgSO_4$, filtered and evaporated in vacuo. The residue was purified by column chromatography (SiO_2, a gradient mixture of toluene and ethyl acetate) to afford **1**. **1a**: Yield, 94%; mp 99–100 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$); δ 8.18 (2H, d, $J = 2.6$ Hz) 7.65 (2H, dd, $J = 8.7$ and 2.6 Hz), 6.71 (2H, d, $J = 8.7$ Hz), 4.62 (4H, s). Anal. calcd for $C_{12}H_{10}Br_2N_2O_2$: C, 38.53; H, 2.69; N, 7.49. Found: C, 38.36; H, 2.70; N, 7.46. **1b**: Yield, 87%. White solid. Mp 101–102 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.16 (2H, d, $J = 2.6$ Hz), 7.63 (2H, dd, $J = 8.8$ and 2.6 Hz), 6.65 (2H, d, $J = 8.8$ Hz), 4.42 (4H, t, $J = 12.5$ Hz), 2.25–2.20 (2H, m). HRMS (EI): calcd for $C_{13}H_{12}Br_2N_2O_2$ (M^+), 387.9245; found, 387.9247. **1c**: Yield, 94%. White solid. Mp 106–107 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.16 (2H, d, $J = 2.6$ Hz), 7.63 (2H, dd, $J = 8.8$ and 2.6 Hz), 6.63 (2H, d, $J = 8.8$ Hz), 4.36–4.29 (4H, m), 1.96–1.89 (4H, m). HRMS (EI): calcd for $C_{14}H_{14}Br_2N_2O_2$ (M^+), 401.9402; found, 401.9402. **1d**: Yield, 76%. White solid. Mp 117–118 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.17 (2H, d, $J = 2.5$ Hz), 7.62 (2H, dd, $J = 8.9$ and 2.5 Hz), 6.63 (2H, d, $J = 8.9$ Hz), 4.29 (4H, t, $J = 13.1$ Hz), 1.86–1.80 (4H, m), 1.62–1.56 (2H, m). HRMS (EI): calcd for $C_{15}H_{16}Br_2N_2O_2$ (M^+), 415.9558; found, 415.9571. **1e**: Yield, 95%. White solid. Mp 111–112 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.17 (2H, d, $J = 2.6$ Hz), 7.62 (2H, dd, $J = 8.9$ and 2.6 Hz), 6.63 (2H, d, $J = 8.9$ Hz), 4.25 (4H, t, $J = 13.2$ Hz), 1.81–1.58 (4H, m), 1.52–1.49 (4H, m). HRMS (EI): calcd for $C_{16}H_{18}Br_2N_2O_2$ (M^+), 429.9715; found, 429.9714.
7. A solution of **1** (9.48×10^{-3} mol), tributylvinyltin (7.21 g, 2.28×10^{-2} mol), $Pd(PPh_3)_4$ (0.84 g, 7.24×10^{-4} mol), and 2,6-di-*tert*-butyl-4-methylphenol (15 mg) in toluene (90 mL) was heated to reflux for 2 h. After the mixture was cooled to ambient temperature, a large excess of 1.2 M aqueous KF solution (75 mL) was added, and the resulting mixture was stirred overnight at the same temperature.

The organic layer was separated from the sludge and aqueous layers, and then dried over $MgSO_4$. The concentrated crude material was purified by column chromatography (SiO_2, a gradient mixture of toluene and ethyl acetate) to afford vinyl compound **2**. **2a**: Yield, 63%. White solid. Mp 65–66 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$); δ 8.10 (2H, d, $J = 2.4$ Hz), 7.70 (2H, dd, $J = 8.5$ and 2.5 Hz), 6.78 (2H, d, $J = 8.5$ Hz), 6.66 (2H, dd, $J = 17.7$ and 11.0 Hz), 5.65 (2H, d, $J = 17.7$ Hz), 5.22 (2H, d, $J = 11.0$ Hz), 4.67 (4H, s). Anal. calcd for $C_{16}H_{16}N_2O_2$: C, 71.62; H, 6.01; N, 10.44. Found: C, 71.68; H, 6.06; N, 10.26. **2b**: Yield, 85%. White solid. Mp 41–42 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.09 (2H, d, $J = 2.4$ Hz), 7.69 (2H, dd, $J = 8.6$ and 2.4 Hz), 6.71 (2H, d, $J = 8.6$ Hz), 6.63 (2H, dd, $J = 17.7$ and 11.0 Hz), 5.63 (2H, d, $J = 17.7$ Hz), 5.20 (2H, d, $J = 11.0$ Hz), 4.47 (4H, t, $J = 12.8$ Hz), 2.28–2.23 (2H, m). HRMS (EI): calcd for $C_{17}H_{18}N_2O_2$ (M^+), 282.1368; found, 282.1368. **2c**: Yield, 71%. White solid. Mp 56–57 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.09 (2H, d, $J = 2.4$ Hz), 7.68 (2H, dd, $J = 8.5$ and 2.4 Hz), 6.69 (2H, d, $J = 8.5$ Hz), 6.64 (2H, dd, $J = 17.7$ and 11.0 Hz), 5.64 (2H, d, $J = 17.7$ Hz), 5.20 (2H, d, $J = 11.0$ Hz), 4.38–4.34 (4H, m), 1.98–1.92 (4H, m). Anal. calcd for $C_{18}H_{20}N_2O_2$: C, 72.95; H, 6.80; N, 9.45, Found: C, 72.74; H, 6.83; N, 9.36. **2d**: Yield, 60%. White solid. Mp 60–61 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.09 (2H, d, $J = 2.5$ Hz), 7.69 (2H, dd, $J = 8.6$ and 2.5 Hz), 6.70 (2H, d, $J = 8.6$ Hz), 6.64 (2H, dd, $J = 17.7$ and 11.0 Hz), 5.63 (2H, d, $J = 17.7$ Hz), 5.20 (2H, d, $J = 11.0$ Hz), 4.31 (4H, t, $J = 13.4$ Hz), 1.88–1.83 (4H, m), 1.65–1.59 (2H, m). Anal. calcd for $C_{19}H_{22}N_2O_2$: C, 73.52; H, 7.14; N, 9.03. Found: C, 73.38; H, 7.23; N, 9.03. **2e**: Yield, 58%. White solid. Mp 43–44 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 8.10 (2H, d, $J = 2.5$ Hz), 7.69 (2H, dd, $J = 8.6$ and 2.5 Hz), 6.69 (2H, d, $J = 8.6$ Hz), 6.62 (2H, dd, $J = 17.7$ and 11.0 Hz), 5.63 (2H, d, $J = 17.7$ Hz), 5.20 (2H, d, $J = 11.0$ Hz), 4.29 (4H, t, $J = 13.4$ Hz), 1.82–1.78 (4H, m), 1.54–1.51 (4H, m). HRMS (EI): calcd for $C_{20}H_{24}N_2O_2$ (M^+), 324.1838; found, 324.1856.

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9. The photocycloaddition was carried out by a conventional method [10] as follows. Into a 1-L flask with a magnetic stirrer and N_2 inlet was placed 1.50×10^{-3} mol of olefin **2** dissolved in acetonitrile (750 mL) and nitrogen gas was bubbled in for 30 min. The solution was irradiated by a 400-W high-pressure mercury lamp through a Pyrex filter. The reaction was monitored by HPLC and TLC. After the disappearance of the olefin (ca. 1.5 h), the reaction mixture was evaporated and then the crude reaction product was purified by column chromatography (SiO_2, a gradient mixture of toluene and ethyl acetate) to afford **3**. **3a**(*exo*,*syn*): Yield, 42%. White solid. Mp 119–120 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$); δ 7.28 (2H, d, $J = 2.5$ Hz), 6.94 (2H, dd, $J = 8.3$ and 2.5 Hz), 6.33 (2H, d, $J = 8.3$ Hz), 5.15 (2H, dd, $J = 14.3$ and 6.3 Hz), 4.40 (2H, dd, $J = 14.3$ and 6.3 Hz), 4.12–4.07 (2H, m), 2.54–2.48 (2H, m), 2.42–2.36 (2H, m). ^{13}C NMR; δ 162.55, 147.77, 135.68, 129.78, 108.41, 68.46, 44.14, 19.80. Anal. Calcd for $C_{16}H_{16}N_2O_2$: C, 71.62; H, 6.01; N, 10.44. Found: C, 71.61; H, 6.01; N, 10.35. **3a**(*anti*): Yield, 42%. White solid. Mp 110–111 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$); δ 7.42 (1H, dd, $J = 8.4$ and 2.5 Hz), 6.99 (1H, dd, $J = 8.4$ and 2.5 Hz), 6.84 (1H, d, $J = 2.5$ Hz), 6.69 (1H, d, $J = 8.4$ Hz), 6.58 (1H, d, $J = 2.5$ Hz), 6.54 (1H, d, $J = 8.4$ Hz), 5.55–5.44 (2H, m), 4.16–4.08 (3H, m), 3.88–3.84 (1H, m), 2.65–2.51 (2H, m), 2.30–2.21 (2H, m). ^{13}C NMR; δ 162.25, 162.17, 148.25, 144.26, 137.90, 134.81, 128.75, 128.17, 110.58, 110.07, 67.07, 66.97, 45.93, 45.22, 20.36, 19.22. Anal. calcd for $C_{16}H_{16}N_2O_2$: C, 71.62; H, 6.01; N, 10.44. Found: C, 71.92; H, 6.20; N, 10.34. **3b**(*exo*,*syn*): Yield, 38%. Pale yellow solid. Mp 138–139 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 7.43 (2H, d, $J = 2.5$ Hz), 7.10 (2H, dd, $J = 8.5$ and 2.5 Hz), 6.34 (2H, d, $J = 8.5$ Hz), 4.79–4.75 (2H, m), 4.14–4.11 (2H, m), 4.01–3.97 (2H, m), 2.60–2.56 (2H, m), 2.45–2.34 (3H, m), 1.95–1.92 (1H, m). ^{13}C NMR ($CDCl_3$) δ 163.43, 148.27, 136.27, 130.30, 110.60, 73.20, 65.36, 42.92, 20.56. HRMS (EI): calcd for $C_{17}H_{18}N_2O_2$ (M^+), 282.1368; found, 282.1369. **3b**(*anti*): Yield, 16%. Pale yellow solid. Mp 118–119 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 7.38 (1H, dd, $J = 8.2$ and 2.4 Hz), 7.24 (1H, d, $J = 2.4$ Hz), 6.97–6.96 (2H, m), 6.64 (1H, d, $J = 8.2$ Hz), 6.49 (1H, d, $J = 8.2$ Hz), 5.19–5.14 (1H, m), 5.06–5.00 (1H, m), 4.12–4.10 (1H, m), 3.97–3.92 (3H, m), 2.67–2.61 (2H, m), 2.36–2.30 (2H, m), 2.07–2.05 (2H, m). ^{13}C NMR ($CDCl_3$) δ 163.16, 163.07, 148.59, 145.24, 138.74, 135.24, 128.90, 128.77, 110.72, 110.36, 61.07 (2C), 44.50, 43.92, 30.36, 20.41, 19.68. Anal. calcd for $C_{17}H_{18}N_2O_2$: C, 72.32; H, 6.43; N, 9.92. Found: C, 72.24; H, 6.51; N, 9.82. **3c**: Yield, 75%. Pale yellow solid. Mp 123–124 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$): **3c**(*exo*,*syn*); δ 7.53 (2H, d, $J = 2.4$ Hz), 7.09 (2H, dd, $J = 8.5$ and 2.4 Hz), 6.38 (2H, d, $J = 8.5$ Hz), 4.68–4.64 (2H, m), 4.05–4.02 (2H, m), 3.98–3.96 (2H, m), 2.54–2.51 (4H, m), 1.86–1.83 (2H, m), 1.45–1.41 (2H, m). **3c**(*endo*,*syn*); δ 7.87 (2H, d, $J = 2.4$ Hz), 6.77 (2H, dd, $J = 8.5$ and 2.4 Hz), 6.29 (2H, d, $J = 8.5$ Hz), 4.68–4.64 (2H, m), 4.05–4.02 (2H, m), 3.98–3.96 (2H, m), 2.42–2.36 (4H, m), 1.86–1.83 (2H, m), 1.45–1.41 (2H, m). **3c**(*anti*); δ 7.53 (1H, dd, $J = 8.5$ and 2.4 Hz), 7.23 (1H, d, $J = 2.4$ Hz), 7.09 (1H, dd, $J = 8.5$ and 2.4 Hz), 7.02 (1H, d, $J = 2.4$ Hz), 6.66 (1H, d, $J = 8.5$ Hz), 6.52 (1H, d, $J = 8.5$ Hz), 4.8–4.76 (2H, m), 4.08–4.02 (1H, m), 3.95–3.88 (2H, m), 3.83–3.79 (1H, m), 2.65–2.57 (2H, m), 2.29–2.23 (2H, m), 2.16–2.14 (1H, m), 2.13–1.97 (1H, m), 1.31–1.23 (2H, m). HRMS (EI): calcd for $C_{18}H_{20}N_2O_2$ (M^+), 296.1525; found, 296.1528. **3d**: Yield, 69%. White solid. Mp 117–118 °C (hexane and acetone). ^{1}H NMR (1,1,2,2-tetrachloroethane-d_2 at 120 °C); δ 7.51 (2H, s), 7.17 (2H, d, $J = 14.0$ Hz), 6.47 (2H, d, $J = 14.0$ Hz), 4.54 (4H, br), 4.03 (2H, s), 2.6–2.5 (4H, m), 1.66–1.57 (4H, m), 1.19–1.09 (2H, m). HRMS (EI): calcd for $C_{19}H_{22}N_2O_2$ (M^+), 310.1681; found, 310.1683. **3e**: Yield, 84%. White solid. Mp 63–64 °C (hexane and acetone). ^{1}H NMR ($CDCl_3$) δ 7.46 (2H, d, $J = 2.4$ Hz), 7.22 (2H, dd, $J = 8.2$ and 2.4 Hz), 6.49 (2H, d, $J = 8.2$ Hz), 4.30–4.26 (4H, m), 3.98–3.95 (2H, m), 2.51–2.42 (4H, m), 1.61–1.57 (4H, m), 1.28–1.22 (4H, m). ^{13}C NMR ($CDCl_3$) $\delta = 162.17$, 146.12, 137.64, 128.57, 110.38, 64.89, 42.52, 28.50, 23.90, 21.75. HRMS (EI): calcd for $C_{20}H_{24}N_2O_2$ (M^+), 324.1837; found, 324.1839.
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11. Pyridinophane **3b**(*exo*,*syn*) or **b**(*anti*) (1.0 mg) was dissolved in hexane (0.30 mL) under a nitrogen atmosphere at 50 °C. By slow evaporation of the solvent under a nitrogen atmosphere at ambient temperature, yellow prismatic crystals were obtained. X-ray crystallographic data of both compounds were obtained on a Rigaku AFC7S instrument. Their structures were solved by direct method and expanded using Fourier techniques (DIRDIF-94 program system). The crystal structural data have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 224546 [**3b**(*exo*,*syn*)] and CCDC 224678 [**3b**(*anti*)].
12. The activation free energies were calculated with chemical shifts of pyridine-ring singlet (neglected the small coupling

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