Pergamon

Tetrahedron, Vol. 53, No. 10, pp. 3557-3570, 1997

0040-4020/97 $17.00 + 0.00

PII: S0040-4020(97)00106-3

Syntheses and Properties of (1,8-Naphthylene)bispyridines and Related Pyridinium Compounds

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Abstract: (1,8-Naphthylene)bispyridines (**1**) and a related pyridinium compound (**2**) were synthesized. X-ray crystallographic analysis showed that the two pyridine rings of a 3,3'-(1,8-naphthylene)bispyridine molecule (**1a**) are in an *anti* conformation. The more intense, bathochromic absorption bands of **1** compared to those of 1-naphthylpyridines (**3**) were attributed to a decrease of the orbital symmetry. The energy barriers of rotational isomerization of **1** and **2** are nearly equal to that of 1,8-bistolylnaphthalene.

Introduction

Despite many attempts to estimate the strength of $\pi \cdot \pi$ interaction between arenes,[1] the nature of interaction between heterocyclic π-systems is still unclear. In 1992, Cozzi *et al.*[2] estimated $\pi \cdot \pi$ interactions between two tolyl rings of 1,8-bis(*o*-tolyl)naphthalenes, emphasizing the importance of a through-space Coulombic force. The crystal structure of pyridine is complicated with 4 molecules per unit cell, contrasting with that of benzene.[3] This complexity in pyridine was interpreted by electronegativity difference between nitrogen and carbon atoms.[4] Rates of conformational flipping for [2.2](2,6)pyridinophane implied that the steric size of a pyridinediyl group was smaller than that of a phenylene group.[5]

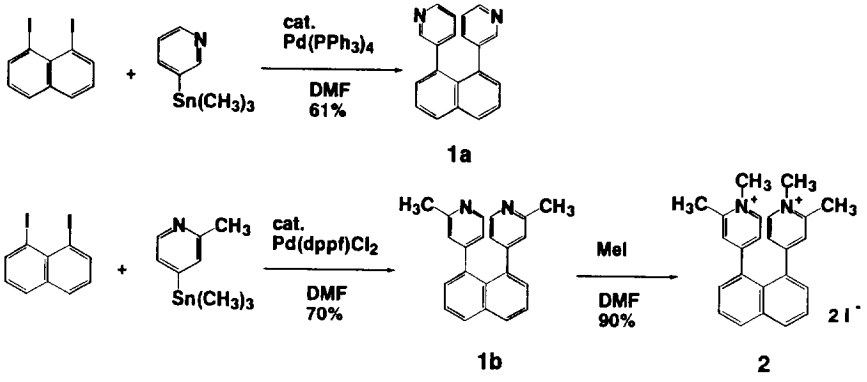
In this paper, we report the syntheses of (1,8-naphthylene)bispyridines and a related pyridinium compound and the estimation of an interaction between two pyridine rings placed close together, demonstrating that the energy barriers of rotational isomerization of (1,8-naphthylene)-bispyridines and a related pyridinium are nearly equal to that of 1,8-bistolylnaphthalene.

Results and Discussion

Syntheses of (1,8-Naphthylene)bispyridines and a Related Pyridinium Compound

3,3'-(1,8-Naphthylene)bispyridine (**1a**)[6] and 4,4'-(1,8-naphthylene)bis(2-methylpyridine) (**1b**) were synthesized by palladium catalyzed Stille coupling reactions[7](Scheme 1). By the reaction with iodomethane, **1b** was converted to the corresponding pyridinium compound **2**.

Scheme 1



3-(1-Naphthyl)pyridine (**3a**) and 2-methyl-4-(1-naphthyl)pyridine (**3b**) were synthesized by palladium catalyzed Suzuki coupling reactions[8] between 1-naphthylboronic acid and halopyridines.

Structure

The X-ray crystallographic analysis of **1a** (Figure 1) revealed that the two pyridine rings were in an *anti* conformation, N13 being opposite to N19 with respect to the plane of the naphthalene nucleus. The selected angles for **1a**, together with those for 1,8-diphenylnaphthalene (**4**),[9] are shown in Table 1. The splay angle (ϕ) and dihedral angle (ψ) of **1a** are larger than the corresponding angles of **4**, while the rotational angles (θ_1, θ_2) of **1a** are smaller than those of **4**.

These structural features suggest that the repulsion between the two pyridine rings in **1a** is larger than that between the two phenyl groups in **4**.

Boekelheide pointed out that steric repulsion between facing aromatic C-H bonds is larger than repulsion between the lone pair of electrons of pyridine rings by showing that the intramolecular distance between the aromatic carbons bearing a hydrogen atom in $[2_4](1,2,4,5)$ cyclophane, 2.950 Å, is longer than that between the two pyridine nitrogen atoms of 5,12-diaza-$[2_4](1,2,4,5)$cyclophane, 2.835 Å.[10]

This Boekelheide's explanation apparently contradicts our observation in 3,3'-(1,8-naphthylene)bispyridine (**1a**). Analogy with the results of pyridinophanes suggests that the splay and dihedral angles for **1a** become smaller than those for **4**, but this is not the case. This discrepancy is attributable to larger structural flexibility in a 1,8-naphthylene system than that in a $[2_4]$cyclophane system. In a $[2_4]$cyclophane system, the relative orientation of the two pyridine rings is fixed in a face-to-face fashion and the main factor affecting the interplaner distance is not a dipole-dipole repulsion. In a 1,8-naphthylene system, however, the two pyridine rings can adopt a splay-out orientation to minimize the sum of the dipole moments of two pyridine rings and the repulsion between lone pairs on nitrogen atoms of two pyridine rings. Thus the interplaner distance depends on both dipole-dipole and steric repulsions.

The ^{1}H NMR spectrum of **1a** in CD_2Cl_2 : CD_3OD (2: 1)[11] at 253 K indicates distinct signals due to two sets of the protons of the pyridine rings (Figure 2). Warming of the sample was accompanied by a coalescence of these signals, which suggested that **1a** existed as a mixture of *syn* and *anti* conformers in solution.

The assignment of the signals of an *anti* conformer was confirmed on the base of the appearance of cross-peaks between 2- and 4-position of the pyridine rings in the ROESY (rotating frame nuclear Overhauser effect spectroscopy) (Figure 2). The *syn/anti* ratio of **1a** in CD_2Cl_2 : CD_3OD (2: 1) was 0.47.

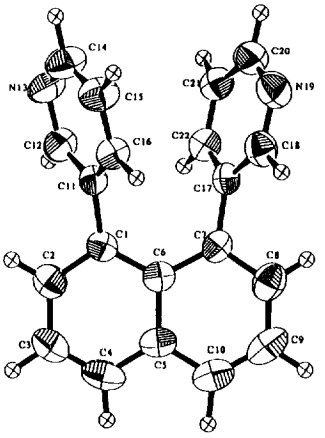
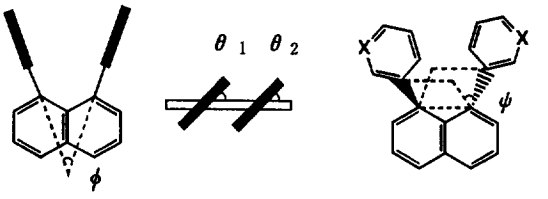


Figure 1. The ORTEP diagram of 3,3'-(1,8-naphthylene)bispyridine (**1a**).

Table 1. Selected angles of crystal structures of 3,3'-(1,8-naphthylene)bispyridine (**1a**) and 1,8-diphenylnaphthalene (**4**).



Compounds	X	Splay(ϕ)[a]	Rotational(θ_1, θ_2)[b]	Dihedral(ϕ)[c]
		degree	degree	degree
1a	N	26	58, 63	12.0
4[d]	CH	20	67, 67	3.4

[a] Splay angle between the pyridine or benzene rings.

[b] Rotational angle of the substituent rings against the naphthalene plane.

[c] Dihedral angle between two single bonds attached to the naphthalene ring.

[d] Taken from ref. 9b.

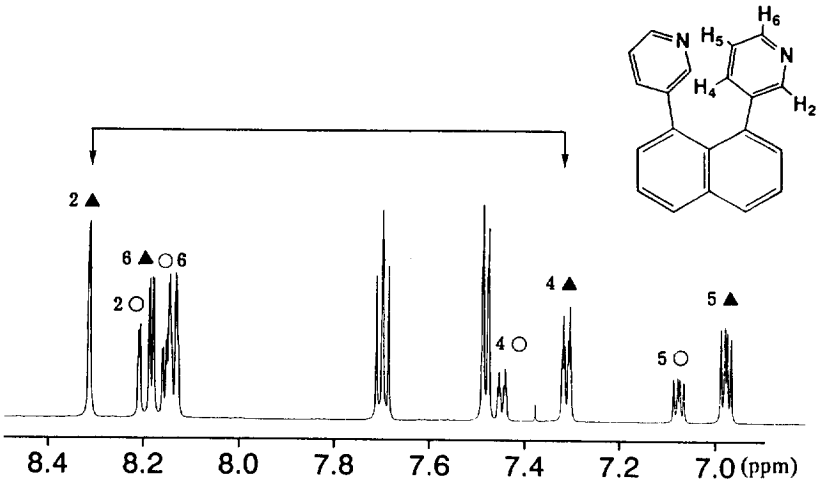


Figure 2. The ^{1}H NMR spectrum of **1a** in CD_2Cl_2 : CD_3OD (2:1) at 253 K. ○ and ▲ stand for the pyridyl protons of *syn* and *anti* conformers, respectively. The arrow indicates the cross-peaks of ROESY.

The *syn/anti* ratio of **1a** increased with the polarity of solvents (Table 2). This is interpreted by the fact that the *syn* conformer, which has larger dipole moments and repulsion between lone pairs of nitrogen atoms than the *anti* conformer, is more effectively stabilized by polar solvents than the *anti* conformer.

The ^{1}H NMR spectra of both 4,4'-(1,8-naphthylene)bis(2-methylpyridine) (**1b**) and bispyridinium (**2**) in CD_2Cl_2 : CD_3OD (2:1) at 273 K indicate two sets of the pyridine rings and methyl groups. Coalescences of these signals on warming show that **1b** and **2** existed as a mixture of *syn* and *anti* conformers in solution. The *syn/anti* ratios of **1b** and **2** were both 1.0 in CD_2Cl_2 : CD_3OD (2:1) and showed no solvent dependence (Table 2), suggesting that the dipole moments of the *syn* conformers are nearly equal to those of the *anti* conformers in **1b** and **2**.

The solvent effect on the *syn/anti* ratio observed for **1a** is another supporting evidence for the importance of the dipole-dipople repulsion in a (1,8-naphthylene)bispyridine system as discussed above.

Table 2. The *syn/anti* ratio of 3,3'-(1,8-naphthylene)bispyridine (**1a**), 4,4'-(1,8-naphthylene)bis(2-methylpyridine) (**1b**), and a bispyridinium (**2**).

Compounds	C_6D_6 [a]	CD_2Cl_2 : CD_3OD (2:1)	CD_3OD	DMF-d_7
1a	0.39	0.47[b]	0.61[a]	0.79[b]
1b	1.0	1.0[a]	1.0[a]	1.0[a]
2		1.0[c]	1.0[b]	1.0[b]

[a] Determined by ^{1}H NMR measurements at 273 K. [b] At 253 K. [c] At 233 K.

Electronic Spectra

In the UV/vis spectra in methanol, the absorption maxima of (1,8-naphthylene)bispyridines, **1a** and **1b**, are bathochromically shifted compared to those of mononaphthylpyridines, **3a** and **3b**, and the extinction coefficients are larger than those of **3a** and **3b** (Figure 3). The calculations of **1a**, **1b**, **3a**, and **3b** with the INDO/S-CI method[12] reproduced these intense and bathochromic absorptions of (1,8-naph- thylene)bispyridines (Table 3).

For all these compounds except **1a**(*anti*), the main absorption was assigned to $\pi \cdot \pi^*$ transitions of the naphthalene moiety based on the INDO/S-CI calculation. The main absorption for **1a**(*anti*) is based upon the two $\pi \cdot \pi^*$ transitions of the pyridine dimer moiety and the naphthalene moiety.

For naphthalene, the two transitions above 300 nm ($b_{1u} \rightarrow b_{2g}$, $a_u \rightarrow b_{3g}$) are symmetry forbidden. In both **1a** and **1b**, the increase in extinction coefficients of the long wavelength absorption based upon the naphthalene π orbitals may be attributed to a decrease in symmetry of π orbital of the naphthalene moiety due to a steric repulsion between the two pyridine rings. The

fact that 1,8-diphenylnaphthalene (**4**) had a larger extinction coefficient than that of 1-phenylnaphthalene was interpreted as the decrease of orbital symmetry due to the steric repulsion.[13] This is also the case for (1,8-naphthylene)bispyridines, **1a** and **1b**.

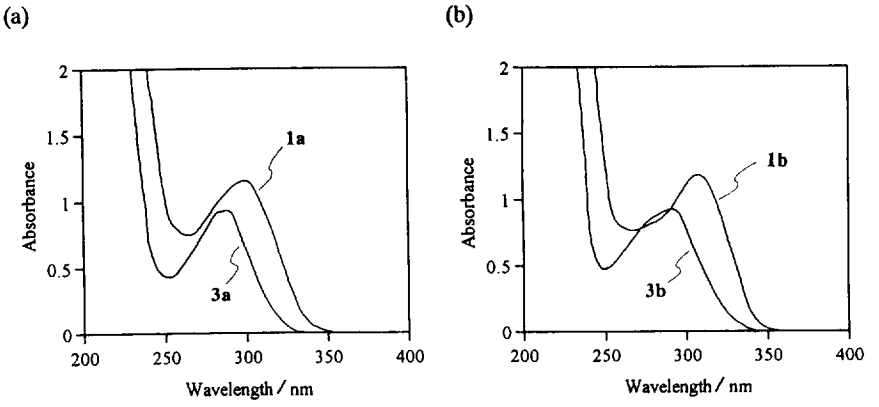


Figure 3. Absorption spectra in methanol at 298 K (1.0×10^{-4} mol $\cdot$dm^{-3}). (a) **1a** and **3a**; (b) **1b** and **3b**.

Table 3. Absorption spectra of **1a**, **1b**, **3a**, and **3b** calculated with the INDO/S-CI method.

Compound[a]	λ_{max} (nm)	f[b]	Transition character[c]	Type[d]
1a(*anti*)	317	0.050	+0.38(H→L+1)-0.71(H→L+3)-0.57(H-2→L)	N
	300	0.058	-0.83(H-1→L+1)+0.34(H-3→L+2)	P
	287	0.020	+0.95(H→L)	N
	284	0.000	+0.57(H-1→L+4)+0.52(H-2→L+5)-0.45(H-3→L+1)	P
	281	0.326	+0.94(H→L)	N
1a (*syn*)	318	0.049	-0.54(H→L+2)-0.50(H→L+3)-0.57(H-2→L)	N
	302	0.012	-0.84(H-1→L+1)	P
	288	0.010	-0.38(H→L+1)+0.44(H-5→L+4)-0.61(H-6→L+1)	N
	286	0.009	-0.53(H-5→L+1)+0.56(H-6→L+4)+0.41(H-7→L+1)	N
	281	0.385	+0.93(H→L)	N
1b (*anti*)	315	0.050	+0.76(H→L+2)-0.56(H-3→L)	N
	290	0.001	-0.71(H-1→L+1)+0.44(H-2→L+3)	P
	282	0.338	+0.95(H→L)	N
1b (*syn*)	315	0.050	-0.74(H→L+2)-0.57(H-3→L)	N
	295	0.000	-0.70(H-1→L+1)+0.40(H-2→L+2)	P
	282	0.338	-0.95(H→L)	N
3a	304	0.015	-0.33(H→L+1)+0.69(H→L+2)+0.51(H-1→L)+0.36(H-2→L)	N+P
	273	0.332	-0.93(H→L)	N
3b	303	0.015	-0.75(H→L+1)-0.53(H-1→L)+0.34(H-2→L)	N+P
	272	0.297	+0.95(H→L)	N

[a] Optimized structures by PM3(CAChe) were used. [b] Oscillator strengths. [c] H and L stand for HOMO and LUMO, respectively. [d] N and P denote $\pi\cdot\pi^*$ transitions of the naphthalene moiety and the pyridyl groups, respectively.

The oscillator strength of the π-π^* transition of the pyridine dimer moiety (HOMO-1 → LUMO+1) in **1a**(*anti*) is larger than that of **1a**(*syn*). This is expained by the difference of orbital symmetry of the pyridine dimer moieties between **1a** (*anti*) and **1a** (*syn*). The angle between the two σ axes of the pyridine rings of **1a** (*anti*) is *ca.* 120° (Figure 4) and the orbitals of the pyridine dimer moieties are unsymmetrical. While the two σ axes of **1a** (*syn*) are parallel and the orbitals of the pyridine dimer moieties are symmetrical (Figure 5).

For both *anti* and *syn* isomers of **1b**, the σ axes of the pyridine rings point to the same directions and their oscillator strengths of the π-π^* transition based on the pyridine dimer moieties are nearly zero. This interpretation of π-π^* transitions of the pyridine dimer moiety in (1,8-naphthylene)bispyridines is consistent with that in [2.2]pyridinophanes.[14]

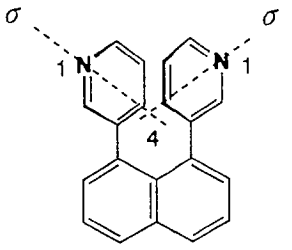


Figure 4. The two σ axes of the pyridine rings of (1,8-naphthylene)bispyridine **1a** (*anti*).

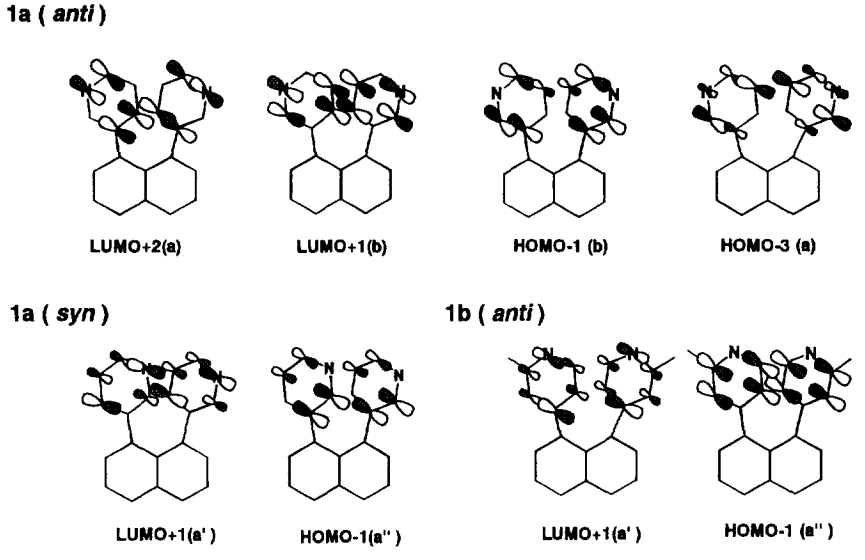


Figure 5. The molecular orbital coefficients of (1,8-naphthylene)bispyridines **1a**(*syn*), **1a**(*anti*), and **1b**(*anti*).

Basicity

The pK_a values of conjugated acids of (1,8-naphthylene)bispyridines (**1a** and **1b**) and the corresponding 1-naphthylpyridines (**3a** and **3b**) are determined by measuring UV absorption spectra at 22 different pH values in a methanolic phosphate buffer (H_2O : methanol = 1:1 by volume) at 293 K. In order to assure the reversibility of the protonations, a titration method was avoided.

The pK_a values of conjugated acids of (1,8-naphthylene)bispyridines (**1a** and **1b**) are 0.3 larger than those of the corresponding 1-naphthylpyridines (**3a** and **3b**), respectively (Table 4). It is known that the pK_a value of conjugated acids of 1,8-bis(dimethylamino)naphthalene,[15] so-called a proton-sponge, is much larger (pK_a = 12.1) than that of dimethylaniline (pK_a = 5.1) because of relief of strain on protonation by forming an intramolecular hydrogen bond. Judging from a difference in pK_a values of conjugated acids between **1a** and **3a** or **1b** and **3b**, (1,8-naphthylene)bispyridines (**1a** and **1b**) fall under ordinary pyridines rather than proton-sponges.

Table 4. The pK_a values of conjugated acids of **1a**, **1b**, **3a**, and **3b**.

Compounds	**1a**	**1b**	**3a**	**3b**
pK_a[a]	4.0	5.2	3.7	4.9

[a] Determined by UV spectroscopic method in H_2O : CH_3OH (1:1) at 293 K.

Energy Barriers of Rotational Isomerization

The ^1H NMR spectra of **1a** in CD_2Cl_2 : CD_3OD (2 : 1) at four different temperature indicate the coalescent process of proton signals for pyridine rings but the signals for naphthalene rings do not change with temperature (Figure 6a). The total lineshape analysis of the pyridine protons of **1a** was made with an ABCD spin system of the DNMR3 program[16] (Figure 6b). The energy barrier of the rotational isomerization from **1a**(*anti*) to **1a**(*syn*) is 65 kJ · mol^{-1} at 300 K (Table 5). The least square analysis indicated that the $\Delta H^{\ddagger}$ is 90 kJ· mol^{-1} and the $\Delta S^{\ddagger}$ is 84 J· mol^{-1}· K^{-1}. The energy barriers for the rotational isomerization of 4,4'-(1,8-naphthylene)bis(2-methylpyridine) (**1b**) and (1,8-naphthylene)bis(*N*-methylpyridinium) **2** were obtained by the coalescence method[17] of variable temperature ^1H NMR measurements using the methyl protons of pyridine rings as a probe (Table 5), together with the energy barrier for 1,8-bis(*m*-tolyl)naphthalene (**6**).[18]

The energy barriers of **1a**, **1b** and **2** are nearly equal to that of **6**. This finding is interesting compared to the results of Cozzi, who reported that in 1,8-bis(*o*-tolyl)naphthalene derivatives the barriers increases monotonically on passing from an electron-donating to an electron withdrawing substituent on aryl groups and this was interpreted in terms of a through-space Coulombic interaction between the two aryl groups.[2] The present results suggest that the strength of π - π interaction between pyridine rings are comparable to that between arenes.

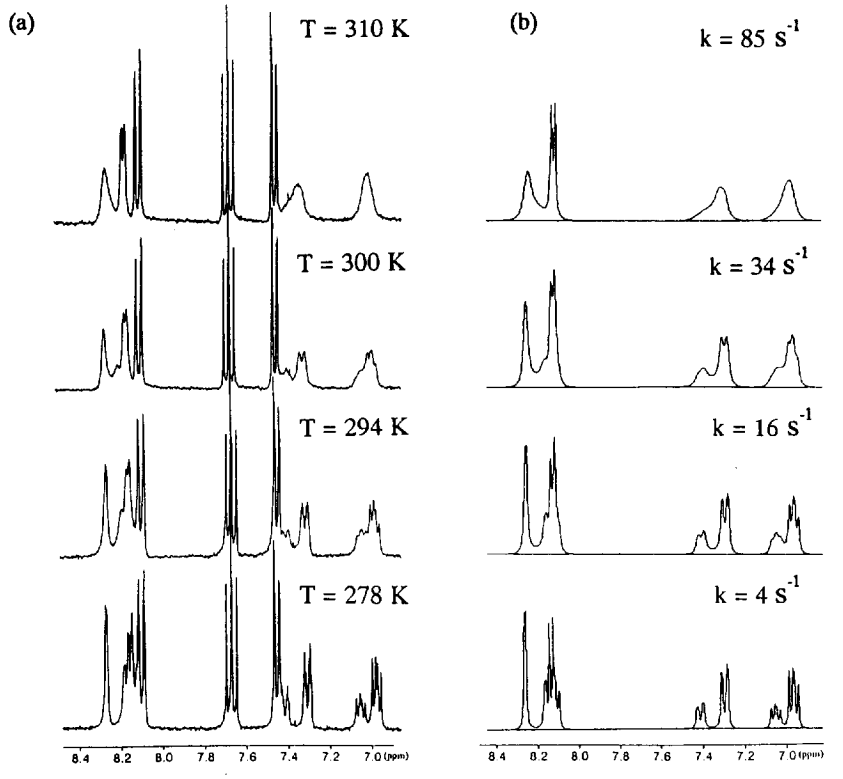


Figure 6. The ^{1}H NMR spectra of **1a** in CD_2Cl_2 : CD_3OD (2 : 1) at various temperature. (a) Observed spectra; (b) Calculated spectra for the pyridyl protons.

Table 5. Energy barriers for the rotational isomerization ($\Delta G^{\ddagger}$) at 300 K of **1a**, **1b**, **2**, and **6**.

Compounds	$\Delta G^{\ddagger}$ / kJ·mol^{-1}		
	CD_2Cl_2 : CD_3OD (2 : 1)	$CDCl_3$	DMF-d_7
1a[a]	65		
1b[b]	64	64	64
2[b]			65
6		65[c]	

[a] Determined by the dynamic ^{1}H NMR method. [b] Determined by the coalescence method. [c] Calculated on the basis of the T_c value in ref. 18.

Conclusion

The two pyridine rings of 3,3'-(1,8-naphthylene)bispyridine (**1a**) are in an *anti* conformation in solid, which is attributed to the dipole-dipole repulsion and the steric repulsion due to lone pairs of nitrogen atoms. The more intense, bathochromic absorption bands of (1,8-naphthylene)bispyridines compared to those of the corresponding 1-naphthylpyridines are interpreted in terms of the decrease in orbital symmetry. The energy barriers for the rotational isomerization of **1a** and 4,4'-(1,8-naphthylene)bis(2-methylpyridine) (**1b**) are comparable with those of tolyl groups.

Experimental

General. Melting points were determined on a Yanaco melting points apparatus and are uncorrected. ^{1}H NMR spectra were recorded on either a Bruker ARX-300 (300MHz) or a Bruker AMX-600 (600MHz) spectrometer and chemical shifts are quoted in ppm downfield from $SiMe_4$. IR spectra were recorded using a JASCO IR-810 spectrometer. UV/vis spectra were recorded on a Shimadzu UV-3100PC spectrometer. EI-Mass spectra and FAB-Mass spectra were measured with a JEOL D-300 spectrometer and a JEOLDX-303 spectrometer, respectively.

3,3'-(1,8-Naphthylene)bispyridine(1a). A solution of 1,8-diiodonaphthalene[9a] (1.4 g, 3.7 mmol), 3-trimethylstannylpyridine[19] (2.3 g, 9.5 mmol), and tetrakis(triphenylphosphine) palladium ($Pd(PPh_3)_4$) (0.20 g, 5 mol%) in DMF (20 ml) was stirred at 140 ℃ for 4 h. The mixture was diluted with an aqueous NH_3 solution, and extracted with CH_2Cl_2. The organic extract was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. Purification by column chromatography on alumina, using first 1:1 hexane-ethyl acetate and then 4:4:1 hexane-ethyl acetate-CH_3OH, gave 3,3'-(1,8-naphthylene)bispyridine (**1a**) (0.55 g, 2.0 mmol, 61 %) as colorless crystals: mp 164 ℃ (hexane-benzene); λ_{max} (CH_3OH) 298 nm (ϵ 11800); ^{1}H NMR (CD_2Cl_2 : CD_3OD = 2 : 1, 253 K) *syn* conformer δ 7.08(dd, 2H, J = 8, 6 Hz), 7.44(dt, 2H, J = 8, 2 Hz), 7.48(d, 2H, J = 8 Hz), 7.69(t, 2H, J = 8 Hz), 8.13 (d, 2H, J = 8 Hz), 8.15(dd, 2H, J = 6, 3 Hz), 8.20(d, 2H, J = 3 Hz); *anti* conformer δ 6.98(dd, 2H, J = 8, 6 Hz), 7.32(dt, 2H,J = 8, 2 Hz), 7.48(d, 2H, J = 8 Hz), 7.69(t, 2H, J = 8 Hz), 8.13 (d, 2H, J = 8 Hz), 8.17(dd, 2H, J = 6, 3 Hz), 8.31(d, 2H, J = 3 Hz); IR (KBr) 3050, 1580, 1500, 1480, 1430, 1410, 1370, 1320, 1185, 1100, 1020, 880 cm^{-1}; MS *m/z* 282 (M^+). Anal. Calcd for $C_{20}H_{14}N_2$: C, 85.12; H, 4.96; N, 9.92. Found: C, 85.39; H, 5.13; N, 9.81.

4,4'-(1,8-Naphthylene)bis(2-methylpyridine)(1b). A solution of 1,8-diiodonaphthalene[9a] (0.30 g, 0.79 mmol), 2-methyl-4-trimethylstannylpyridine[20] (0.60 g, 2.4 mmol), and diphenylphosphinoferrocene palladium dichloride ($Pd(dppf)Cl_2$) (40 mg, 7 mol%) in DMF (3 ml) was stirred at 140 ℃ for 4 h. The mixture was diluted with an aqueous NH_3 solution, and extracted with CH_2Cl_2. The organic extract was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. Purification by column chromatography on alumina, using first 1:1 hexane-ethyl

acetate and then 4:4:1 hexane-ethyl acetate-CH_3OH, gave 4,4'-(1,8-naphthylene)bis(2-methylpyridine) (**1b**) (0.17 g, 0.56 mmol, 70 %) as colorless crystals: mp 141 ℃ (hexane-benzene); λ_{max} (CH_3OH) 306 nm (ϵ 11900); ^{1}H NMR(CD_2Cl_2 : CD_3OD = 2 : 1, 273 K) one isomer δ 2.22(s, 6H), 6.62(s, 2H), 7.08(d, 2H, J = 2 Hz), 7.47(d, 2H, J = 8 Hz), 7.70(t, 2H, J = 8 Hz), 8.10(d, 2H, J = 8 Hz), 8.21(d, 2H, J = 2 Hz); the other isomer δ 2.40(s, 6H), 6.87(s, 2H), 6.96(d, 2H, J = 2 Hz), 7.47(d, 2H, J = 8 Hz), 7.70(t, 2H, J = 8 Hz), 8.01(d, 2H, J = 2 Hz), 8.10(d, 2H, J = 8 Hz); IR (KBr) 3050, 1930, 1602, 1542, 1510, 1450, 1402, 1340, 1290, 1260, 1120, 1020, 880 cm^{-1}; MS *m/z* 310 (M^+). Anal. Calcd for $C_{22}H_{18}N_2 \cdot 0.6H_2O$: C, 82.26; H, 6.02; N, 8.72. Found: C, 82.26; H, 6.02; N, 8.73.

4,4'-(1,8-Naphthylene)bis(1,2-dimethylpyridinium) diiodide(2). A solution of **1b** (50 mg, 0.16 mmol) and iodomethane (0.36 g, 2.6 mmol) in DMF (1 ml) was stirred at 140 ℃ for 2 h. After cooling, the mixture was diluted with diethyl ether (2 ml), and the precipitate was filtered and washed with diethyl ether to gave 4,4'-(1,8-naphthylene)bis(1,2-dimethylpyridinium) diiodide (**2**) (86 mg, 0.14 mmol, 90 %) as pale yellow crystals: mp 246 ℃(dec.); λ_{max} (CH_3OH) 356 nm (ϵ 14600); ^{1}H NMR(CD_2Cl_2 : CD_3OD = 2 : 1, 233 K) one isomer δ 2.90(s, 6H), 4.28(s, 6H), 7.58(dd, 2H, s, J = 6, 2 Hz), 7.78(d, 2H, J = 8 Hz), 7.88(t, 2H, J = 8 Hz), 7.96(d, 2H, J = 2 Hz), 8.32(d, 2H, J = 8 Hz), 8.70(d, 2H, J = 6 Hz); the other isomer δ 3.01(s, 6H), 4.30(s, 6H), 7.70(dd, 2H, J = 6, 2 Hz), 7.78(d, 2H, J = 8 Hz), 7.86(d, 2H, J = 2 Hz), 7.88(t, 2H, J = 8 Hz), 8.32(d, 2H, J = 8 Hz), 8.74(d, 2H, J = 6 Hz); IR (KBr) 3410, 1640, 1560, 1520, 1460, 1390, 1302, 830 cm^{-1}; FAB-MS *m/z* 467 (M^+-I). Anal. Calcd for $C_{24}H_{24}I_2N_2 \cdot H_2O$: C, 47.08; H, 4.28; N, 4.58. Found: C, 46.99; H, 4.14; N, 4.59.

3-(1-Naphthyl)pyridine(3a). To a solution of 3-bromopyridine(0.80 g, 5.2 mmol) and $Pd(PPh_3)_4$ (0.18 g) in toluene (10 ml) and 1 M aqueous Na_2CO_3 (10 ml), was added 1-naphthylboronic acid[21] (0.90 g, 5.2 mmol) in CH_3OH (4 ml) at 80 ℃, and the mixture was stirred at 80 ℃ for 1.5 h. After cooling, the mixture was extracted with CH_2Cl_2. The organic extract was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. Purification by column chromatography on alumina, using 4:1 hexane-ethyl acetate, gave 3-(1-naphthyl)pyridine (**3a**) (0.72 g, 68 %) as a colorless oil; λ_{max}(CH_3OH) 288 nm (ϵ 9400); ^{1}H NMR($CDCl_3$) δ 7.4-7.6(m, 5H), 7.80-7.86(m, 2H), 7.92(d, 1H, J = 5 Hz), 7.94(dd, 1H,J = 6, 1 Hz), 8.69(dd, 1H,J = 6, 1 Hz), 8.76(d, 1H, J = 1 Hz); IR (KBr) 3050, 1595, 1560, 1505, 1480, 1412, 1398, 1320, 1250, 1192, 1020, 960, 800 cm^{-1}; MS *m/z* 205 (M^+). Anal. Calcd for $C_{15}H_{11}N$: C, 87.77; H, 5.40; N, 6.82. Found: C, 87.56; H, 5.46; N, 6.76.

2-Methyl-4-(1-naphthyl)pyridine(3b). To a solution of 4-bromo-2-methylpyridine[22] (0.86 g, 5.2 mmol) and $Pd(PPh_3)_4$ (0.18 g) in toluene (10 ml) and 1 M aqueous Na_2CO_3 (10 ml), was added 1-naphthylboronic acid[21] (0.90 g, 5.2 mmol) in MeOH (4 ml) at 80 ℃, and the mixture was stirred at 80 ℃ for 4 h. After cooling, the mixture was extracted with CH_2Cl_2. The organic extract was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. Purification by column chromatography on alumina, using 4:1 hexane-ethyl acetate, gave 2-methyl-4-(1-naphthyl)pyridine (**3b**) (1.02 g, 90 %) as colorless crystals: mp 58 ℃(hexane); λ_{max} (CH_3OH) 291 nm

(ε 9100); ^{1}H NMR($CDCl_3$) δ 2.68(s, 3H), 7.25-7.6(m, 6H), 7.84(d, 1H, J = 8.1 Hz), 7.88-7.95(m, 2H), 8.61(d, 1H, J = 4.8 Hz); IR (KBr) 3050, 1930, 1602, 1542, 1510, 1450, 1402, 1340, 1290, 1260, 1120, 1020, 880, 840 cm^{-1}; MS *m/z* 219 (M^+). Anal. Calcd for $C_{16}H_{13}N$: C, 87.77; H, 5.40; N, 6.82. Found: C, 87.56; H, 5.46; N, 6.76.

Single Crystal X-ray Diffraction Analysis of 1a. The X-ray diffraction data collection of **1a** was performed on a Rigaku AFC-5R diffractometer using monochromated Cu-Kα radiation and a scan width of (1.15 + 0.3 tan θ)° within 2 θ < 120.3°. The structure was solved by SHELXS86[23] and refined by a full-matrix least-squares procedure to the final R factor of 0.037. *Crystal data* : monoclinic, $P2_1/n$, a = 11.408(1), b = 9.796(2), c = 13.324(1) Å, β = 102.413(9)°, Z = 4, D_{calc} = 1.418 g•dm^{-3}; μ(Cu-Kα) = 6.04 cm^{-1}, F(000) = 656, T = 302 K, total unique data 2316, No. of observations [$I \geqq 3\sigma(I)$] 1273, R = 0.037, R_w = 0.029.

Determination of pK_as of Conjugate Acids of Pyridines. Twenty two methanolic solutions of phosphate buffer (H_2O : methanol = 1 : 1 by volume) having different pH values from 3.4 to 12.1 were prepared. The absorption spectra of pyridines in each solutions were measured and showed the isosbestic points. The pK_as of the acids were determined based on a plot of pH vs. absorbance.

Determination of Rotational Barriers by Dynamic NMR Method. The lineshape analysis of **1a** was performed on a NEC PC9821V13 personal computer using the DNMR3K program, which is a modified version of the DNMR3 program[16] by Dr. H. Kihara of Hyogo University of Teacher Education. The T_2 values were estimated from the half widths of TMS signals and temperatures were calibrated using an ethylene glycol. The rate constants k were obtained using the program of an ABCD spin system.

Determination of Rotational Barriers by Coalescence Method. The rotational barriers were estimated based upon equation (1)[17] where $\Delta\nu$ is the chemical shift difference between the individual rotameric signals of methyl groups and T_c is the temperature of coalescence.

$$\Delta G^{\ddagger} = 19.14\ T_c\ (9.97+\log(T_c/\Delta\nu))\quad J\cdot mol^{-1} \qquad (1)$$

Data : **1b** (CD_2Cl_2 : CD_3OD = 2 : 1) $\Delta\nu$= 54 Hz, T_c = 310 K; ($CDCl_3$) $\Delta\nu$= 39 Hz, T_c = 307 K; (DMF-d_7) $\Delta\nu$= 48 Hz, T_c = 310 K; **2** (DMF-d_7) $\Delta\nu$= 9.9 Hz, T_c = 296 K.

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(*Received in Japan* 6 *November* 1996; *accepted* 23 *January* 1997)