Inorg. Chem. **2003**, *42*, 7932–7937

Inorganic Chemistry

Article

Luminescent Lanthanide Complexes with Stereocontrolled Tris(2-pyridylmethyl)amine Ligands: Chirality Effects on Lanthanide Complexation and Luminescence Properties

Takashi Yamada,[†] Satoshi Shinoda,[†] Hideki Sugimoto,[†] Jun-ichi Uenishi,[‡] and Hiroshi Tsukube*,[†]

Department of Chemistry, Graduate School of Science, Osaka City University,
Sugimoto, Sumiyoshi-ku, Osaka 558-8585, Japan, and Department of Pharmaceutical Organic
Chemistry, Kyoto Pharmaceutical University, Misasagi, Yamashina, Kyoto 607-8412, Japan

Received December 24, 2002

A series of tris(2-pyridylmethyl)amines including one and two asymmetric centers were synthesized in a stereocontrolled fashion as potential ligands of lanthanide cations. The reaction of chiral pyridylethyl methanesulfonates and bis(pyridylmethyl)amines occurred via an S_N2 mechanism with complete inversion of asymmetric centers and gave the stereocontrolled tris(2-pyridylmethyl)amines, the stereochemical purity of which was ascertained by GPC, NMR, X-ray, and polarimetry experiments. They formed stable Tb^{3+} and Eu^{3+} complexes having 1:1, 1:2, and 1:3 stoichiometry (metal:ligand) in CH_3CN solutions. NMR and UV titration experiments revealed that their complexation behaviors were rarely influenced by ligand chirality but significantly affected by the nature of the counteranion and the concentration ratio of metal to ligand. The Tb^{3+} and Eu^{3+} complexes with these tripodal ligands exhibited characteristic luminescence spectra upon excitation for pyridine chromophores (260 nm), the intensities of which were largely dependent on the ligand chirality. The meso isomer of the disubstituted tripods particularly exhibited the enhanced terbium luminescence ca. three times more than its diastereomer and un- and monosubstituted tripods. Direct excitation at the lanthanide center had similar chirality effects on the luminescence profiles, indicating that the stereochemistry of the employed ligand largely influenced the lanthanide emitting processes. Since the ligand chirality finely modified the local coordination environments around the lanthanide center, the use of stereocontrolled ligands is applicable in design of the luminescent lanthanide complexes.

Introduction

Ligand chirality is one of the most important structural factors in the design of functional metal complexes. Various metal complexes have featured chiral ligands and successfully been employed in asymmetric catalysis, enantiomer-selective extraction, chirality sensing, biomimetic modeling, and other chemical systems.[1] Although most of the synthetic chiral ligands are limited to use in the asymmetric processes, several biological chiral ligands exhibit excellent functions in the nonasymmetric processes.[2] Lasalocid is a typical example of naturally occurring ionophores which mediate biomembrane transport of "achiral" metal cations. This has a series of asymmetric carbons in the acyclic ligand skeleton and acts as a receptor of spherical Na^+ cation. Still et al. compared the cation binding abilities of several stereoisomers of the lasalocid.[3] Although it does not target chiral substrates in nature, their metal binding experiments suggested that the optimization of ligand stereochemistry highly enhanced the ionophoric functions. We previously developed new types of Ag^+ ion-specific podands having chiral pyridine moieties and found that a proper selection of the ligand chirality led to high Ag^+ ion binding ability.[4] Therefore, the use of chiral ligands offers an unexplored but promising approach in the development of intelligent metal complexes with highly sophisticated functions.[5]

---

* To whom correspondence should be addressed. E-mail: tsukube@sci.osaka-cu.ac.jp. Fax: +81-6-6605-2560.

[†] Osaka City University.

[‡] Kyoto Pharmaceutical University.

(1) Reviews of chiral lanthanide complexes: (a) Aspinall, H. C. *Chem. Rev.* **2002**, *102*, 1807−1850. (b) Tsukube, H.; Shinoda, S. *Chem. Rev.* **2002**, *102*, 2389−2403.

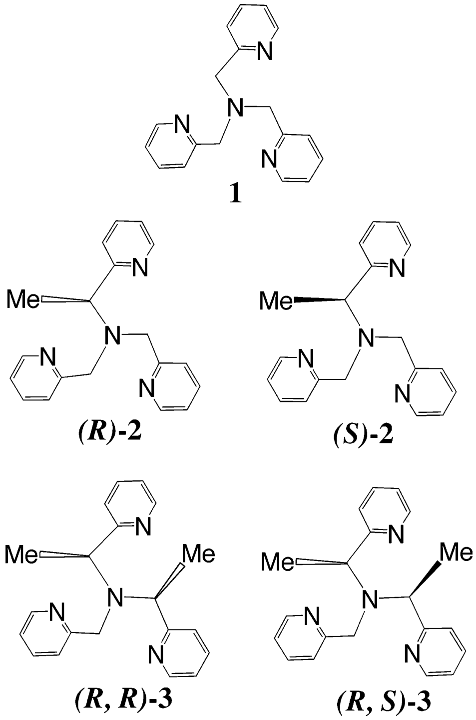
(2) Review: Tsukube, H.; Yamada, T.; Shinoda, S. *Ind. Eng. Chem. Res.* **2000**, *39*, 3412−3418.

(3) Erickson, S. D.; Still, W. C. *Tetrahedron Lett.* **1990**, *31*, 4253−4256.

(4) Tsukube, H.; Shinoda, S.; Uenishi, J.; Hiraoka, T.; Imakoga, T.; Yonemitsu, O. *J. Org. Chem.* **1998**, *63*, 3884−3894.

10.1021/ic020726r CCC: $25.00

Here, we report the stereocontrolled synthesis of tris(2-pyridylmethyl)amine ligands and interesting effects of ligand chirality on lanthanide complexation and luminescence phenomena.[6] Various tripodal ligands have been developed in which phosphorus donors, pyrazoyl groups, alkoxides, triamines, triamides, tripyridines, and other donor groups were incorporated.[7] Tris(2-pyridylmethyl)amine derivatives are well-characterized tripods,[8] but only a few examples of their chiral versions have been reported. Canary et al. presented a tris(2-pyridylmethyl)amine derivative having one asymmetric center as a chromophoric ligand for metal complex devices.[9] Another type of tris(2-pyridylmethyl)-amine which included a *cis*- or *trans*-piperidine skeleton was recently fabricated.[10] The cis ligand of this type worked as a fluorescent sensor specific for Zn^{2+} ion, while the corresponding trans isomer did not operate. We prepare below a series of stereoisomers of tris(2-pyridylmethyl)amines by combining lipase-catalyzed optical resolution and an S_N2-type replacement reaction. They provide new insights into the ligand chirality effects on lanthanide complexation and luminescence behaviors. Although some chiral lanthanide complexes were reported to exhibit stereoselective luminescence quenching behaviors with chiral metal complexes,[11] we demonstrate here that the use of stereocontrolled ligands offers an effective method to develop the luminescent lanthanide complexes.


1

***(R)*-2**

***(S)*-2**

***(R, R)*-3**

***(R, S)*-3**

Figure 1. Tris(2-pyridylmethyl)amine ligands having stereocontrolled substituents.

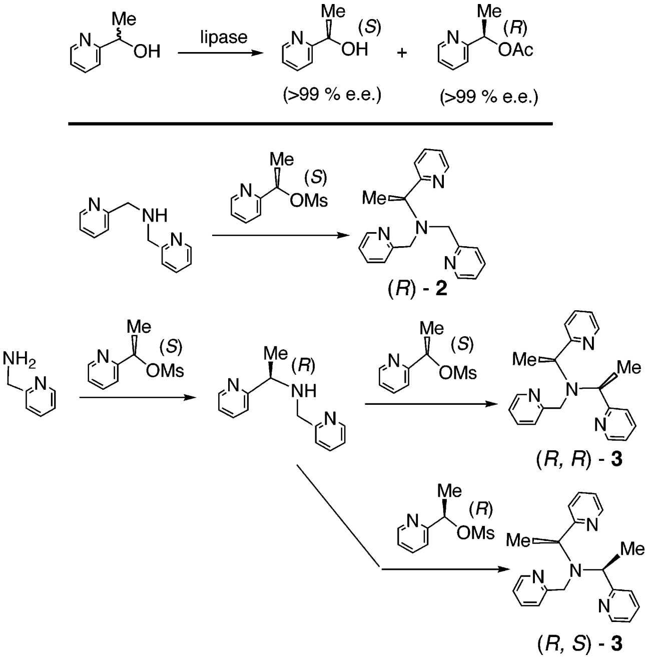


Figure 2. Stereocontrolled synthesis of tris(2-pyridylmethyl)amine ligands.

Results and Discussion

1. Synthesis of Stereocontrolled Tris(2-pyridylmethyl)-amine Ligands. We prepared tris(2-pyridylmethyl)amines having one and two chiral substituents on the tripodal skeleton (Figures 1 and 2). The kinetic resolution of racemic pyridylethanol was successfully performed by *Candida antarctia* lipase with vinyl acetate in diisopropyl ether and gave both enantiomers with > 99% ee in quantitative yields.[12] Tris(2-pyridylmethyl)amine derivatives were derived from chiral pyridylethyl methanesulfonates and corresponding bis(pyridylmethyl)amines or pyridylmethylamine[13] (Figure 2). Monosubstituted derivative (*R*)-**2** was prepared from (*S*)-1-(2-pyridyl)ethyl methanesulfonate and bis(pyridyl-

---

(5) Effects of stereocontrolled substitution on cation binding phenomena were reported in other ligand systems: (a) Sasaki, S.; Naito, H.; Maruta, K.; Kawahara, E.; Maeda, M. *Tetrahedron Lett*. **1994**, *35*, 3337−3340. (b) Shibutani, Y.; Mino, S.; Long, S.; Moriuchi-Kawakami, T.; Yakabe, K.; Shono, T. *Chem. Lett.* **1997**, 49−50.

(6) Preliminary Communication: Yamada, T.; Shinoda, S.; Uenishi, J.; Tsukube, H. *Tetrahedron Lett*. **2001**, *42*, 9031−9033.

(7) Recent examples of tripodal ligands for lanthanide cations: (a) Renaud, F.; Piguet, C.; Bernardinelli, G.; Bunzli, J. C. G.; Hopfgartner, G. *J. Am. Chem. Soc.* **1999**, *121*, 9326−9342. (b) Johnson, A. R.; O'Sullivan, B.; Raymond, K. N. *Inorg. Chem.* **2000**, *39*, 2652−2660. (c) Mazzanti, M.; Wietzke, R.; Pecaut, J.; Latour, J.-M.; Maldivi, P.; Remy, M. *Inorg. Chem.* **2002**, *41*, 2389−2399. (d) Flanagan, B. M.; Bernhardt, P. V.; Krausz, E. R.; Luthi, S. R.; Riley, M. J. *Inorg. Chem.* **2002**, *41*, 5024−5033.

(8) Recent examples of transition metal complexes with tris(2-pyridylmethyl)amine ligands: (a) Chen, K.; Costas, M.; Que, Jr. L. *J. Chem. Soc., Dalton Trans.* **2002**, 672−679. (b) Ogo, S.; Yamahara, R.; Roach, M.; Suenobu, T.; Aki, M.; Ogura, T.; Kitagawa, T.; Masuda, H.; Fukuzumi, S.; Watanabe, Y. *Inorg. Chem.* **2002**, *41*, 5513−5520. (c) Zahn, S.; Canary, J. W. *J. Am. Chem. Soc.* **2002**, *124*, 9204−9211.

(9) (*R*)-**2** was derived from chiral 1-(2-pyridyl)ethylamine, and its copper complex was characterized: Canary, J. W.; Allen, C. S.; Castagnetto, J. M.; Chiu, Y.-H.; Toscano, P. J.; Wang, Y. *Inorg. Chem.* **1998**, *37*, 6255−6262.

(10) Dai, Z.; Xu, X.; Canary, J. W. *Chem. Commun.* **2002**, 1414−1415.

(11) (a) Metcalf, D. H.; Bolender, J. P.; Driver, M. S.; Richardson, F. S. *J. Phys. Chem.* **1993**, *97*, 553−564. (b) Meskers, S. C. J.; Ubbink, M.; Canters, G. W.; Dekkers, H. P. J. M. *J. Phys. Chem.* **1996**, *100*, 17957−17969. (c) Bobba, G.; Frias, J. C.; Parker, D. *Chem. Commun.* **2002**, 890−891.

(12) Uenishi, J.; Hiraoka, T.; Hata, S.; Nakanishi, K.; Yonemitsu, O.; Nakamura, K.; Tsukube, H. *J. Org. Chem.* **1998**, *63*, 2481−2487.

(13) Synthesis of chiral 1-(2-pyridyl)ethyl methanesulfonate esters and their substitution reactions: Uenishi, J.; Takagi, T.; Ueno, Y.; Hiraoka, T.; Yonemitsu, O.; Tsukube, H. *Synlett* **1999**, 41−44.

methyl)amine in 30% yield. Its molar circular dichromic absorption $\Delta\epsilon$ at 267 nm was recorded as $+3.60$ cm^2 mmol^{-1} (1.00×10^{-4} mol/L in CH_3OH), which was comparable with that reported by Canary et al. ($\Delta\epsilon = +3.55$ cm^2 mmol^{-1}, 1.00×10^{-4} mol/L in CH_3OH).[9] Disubstituted ligand (*R*,*R*)-**3** was newly synthesized by one-step reaction of excess (*S*)-1-(2-pyridyl)ethyl methanesulfonate with 2-aminomethylpyridine, while its diastereomer (*R*,*S*)-**3** was obtained by successive substitution reactions (Figure 2). Their stereochemical purity was determined to be >95% de for (*R*,*S*)- and (*R*,*R*)-**3** by GPC (JAIGEL-1H and -2H, Japan Analytical Ind. $CHCl_3$) and NMR determinations. The stereochemistry of (*R*,*S*)-**3** was also confirmed by X-ray crystal structure analysis (Figure S1 in the Supporting Information).[14] Since this was prepared from *N*-(2-pyridylmethyl)-(*R*)-1-(2-pyridyl)ethylamine and (*R*)-1-(2-pyridyl)ethyl methanesulfonate, the substitution on the nitrogen atom was confirmed to proceed via S_N2 mechanism with complete inversion of the asymmetric center. Thus, tripods **2** and **3** have sufficient stereochemical purity to evaluate the chirality effects on lanthanide complexation and luminescence profiles. Tris[1-(2-pyridyl)ethyl]amines having three chiral substituents could not be obtained using successive S_N2 reactions between corresponding 1-(2-pyridyl)ethyl methanesulfonates and 1-(2-pyridyl)ethylamines. Since such multiple substitution may have several steric problems, we further attempted high-pressure reaction conditions (in THF, CH_3OH, or $CHCl_3$; 0.7 GPa; 30−100 °C)[15] but got only undesired products. Therefore, we compare here lanthanide complexation and luminescence behaviors of un-, mono-, and disubstituted tripods **1**−**3**.

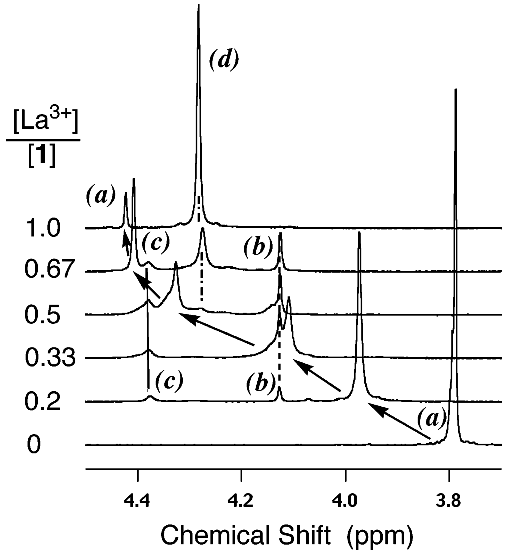


Figure 3. ^{1}H NMR spectral changes of $-CH_2-$ proton signals of tripod **1** upon addition of lanthanum triflate in CD_3CN: tripod **1**, 0.005 mol/L; $La(CF_3SO_3)_3$, 0−0.005 mol/L.

2. Lanthanide Complexation with Tris(2-pyridylmethyl)amine Ligands. Some tris(2-pyridylmethyl)amine derivatives having no asymmetric carbon were reported to form stable complexes with lanthanide cations.[16] Mazzanti et al. determined crystal structures of $EuCl_3$, $TbCl_3$, $LuCl_3$, and $NdCl_3$ complexes with unsubstituted tripod **1** and applied this ligand in the extraction of actinides. Su and Kang characterized crystal structures and luminescence properties of lanthanide complexes with bis(2-benzimidazolymethyl)-(2-pyridylmethyl)amine. They used lanthanide chloride and nitrate salts and confirmed that 1:1 complexes (metal:ligand) predominantly formed in both solid and solution states. Since these anions occupied three coordination sites on the lanthanide center, they favored 1:1 complexes between lanthanide cation and tris(2-pyridylmethyl)amine derivatives. In contrast, our NMR and UV titration experiments with lanthanide triflates demonstrated that 1:2 and 1:3 complexations also occurred in the presence of excess ligand. Figure 3 illustrates typical ^{1}H NMR spectral changes of methylene protons upon lanthanum complexation. Upon addition of increasing amounts of lanthanum triflate to an CH_3CN solution of tripod **1**, both shifted (***a***) and separated signals (***b***−***d***) for methylene protons were observed in several mixtures. Signal ***a*** shifted continuously and disappeared at the mole ratio of $[La^{3+}]/[\mathbf{1}] > 1.2$, where only signal ***d*** was observed. The plot of the shifted values of signal ***a*** vs $[La^{3+}]/[\mathbf{1}]$ had breaks around the mole ratios of 0.33 and 0.50, while signals ***b*** and ***c*** appeared at the mole ratio ranging between 0.2 and 1.0. Since the weakly coordinating triflate anion was easily exchanged,[17] these spectral changes revealed that 1:3, 1:2, and 1:1 complexes formed successively. Figure 3 also indicates that ligand exchange rate in the 1:3 complex is faster than NMR time scale, though 1:1 and 1:2 complexes exhibit slow kinetics. Although their 1:3 complexes had dynamic coordination natures and were not isolated, they were detected by the ESI−MS method. The peak due to $[M + 3\text{tripod} + 2CF_3SO_3 + CH_3CN]^+$ was typically observed at *m*/*z* 1435, when terbium triflate was mixed with 3 equiv of tripod (*R*,*R*)- or (*R*,*S*)-**3** in CH_3CN (Figure S2 in the Supporting Information). Thus, we assume the stepwise equilibria described below, in which the stepwise formation constants K_1, K_2, and K_3 of lanthanide

---

(14) A single crystal of (*R*,*S*)-**3** was mounted on glass fiber and cooled in a stream of dinitrogen (−100 °C). Its X-ray data were collected with graphite-monochromated Mo K radiation on a Rigaku/MSC Mercury CCD system. The structure was solved by direct methods (DIRDIF) and expanded using Fourier techniques. The non-hydrogen atoms were refined anisotropically by the full-matrix least-squares method of Shelex-97. Hydrogen atoms were located on calculated positions and not refined. All calculations were performed using TEXSAN. The crystallographic data: monoclinic ($P2_1/n$), $a = 11.974(3)$, $b = 10.163(3)$, $c = 14.263(4)$, $\beta = 90.064(6)$, $Z = 4$, R_1 (wR_2) = 3.5 (11.4) %. Other data were deposited in the CCDC: (a) Beurskens, P. T.; Admiraal, G.; Beurskens, G.; Bosman, W. P.; de Gelder, R.; Israel, R.; Smits, J. M. M. *The DIRDIF-94 Program System*; Technical Report; Crystallography Laboratory: University of Nijmegen, Nijmegen, The Netherlands, 1994. (b) Sheldrick, M. *Program for the Refinement of Crystal Structures*; University of Goettingen, Goettingen, Germany, 1997. (c) *TEXSAN. Single-Crystal Structure Analysis Package*; Molecular Structure Corp.: The Woodlands, TX 77382, 1992.

(15) Matsumoto, K.; Hashimoto, M.; Toda, M.; Tsukube, H. *J. Chem. Soc., Perkin Trans. 1* **1995**, 2497−2502.

(16) (a) Wietzke, R.; Mazzanti, M.; Latour, J.-M.; Pecaut, J.; Cordier, P.-Y.; Madic, C. *Inorg. Chem.* **1998**, *37*, 6690−6697. (b) Yang, X.-P.; Su, C.-Y.; Kang, B.-S.; Feng, X.-L.; Xiao, W.-L.; Liu, H.-Q. *J. Chem. Soc., Dalton Trans.* **2000**, 3253−3260. (c) Wietzke, R.; Mazzanti, M.; Latour, J.-M.; Pecaut, J. *J. Chem. Soc., Dalton Trans.* **2000**, 4167−4173. (d) Mazzanti, M.; Wietzke, R.; Pecaut, J.; Latour, J.-M.; Maldivi, P.; Remy, M. *Inorg. Chem.* **2002**, *41*, 2389−2399.

Table 1. Stepwise Formation Constants for Complexation between Tris(2-pyridylmethyl)amine Ligands and Lanthanide Cations (Eu^{3+} and Tb^{3+})

	1	(*R*)-**2**	(*R*,*R*)-**3**	(*R*,*S*)-**3**
		"Eu^{3+} Complexes"		
$\log K_1$	7.5 ± 0.4	7.4 ± 0.3	6.9 ± 0.2	6.7 ± 0.3
$\log K_2$	5.2 ± 0.2	5.6 ± 0.2	5.3 ± 0.3	5.5 ± 0.4
$\log K_3$	5.3 ± 0.3	5.4 ± 0.2	5.6 ± 0.1	5.7 ± 0.5
		"Tb^{3+} Complexes"		
$\log K_1$	8.1 ± 0.2	7.9 ± 0.4	7.1 ± 0.3	7.0 ± 0.1
$\log K_2$	5.4 ± 0.2	5.3 ± 0.2	5.0 ± 0.3	5.7 ± 0.4
$\log K_3$	5.4 ± 0.1	5.8 ± 0.3	6.1 ± 0.4	6.2 ± 0.1

cation M with tris(2-pyridylmethyl)amine L are defined by eqs 1−3.

$$\mathrm{M} + \mathrm{L} = \mathrm{ML} \quad K_1 = \frac{[\mathrm{ML}]}{[\mathrm{M}][\mathrm{L}]} \tag{1}$$

$$\mathrm{ML} + \mathrm{L} = \mathrm{ML_2} \quad K_2 = \frac{[\mathrm{ML_2}]}{[\mathrm{ML}][\mathrm{L}]} \tag{2}$$

$$\mathrm{ML_2} + \mathrm{L} = \mathrm{ML_3} \quad K_3 = \frac{[\mathrm{ML_3}]}{[\mathrm{ML_2}][\mathrm{L}]} \tag{3}$$

Tris(2-pyridylmethyl)amine ligands **1**−**3** exhibited characteristic UV absorption bands due to the pyridine chromophores in CH_3CN, which were significantly perturbed upon complexation with Eu^{3+} and Tb^{3+} cations. When the absorbance changes at 260 or 269 nm were plotted against a function of added amounts of lanthanide triflates, each titration curve had sigmoidal shape and gave good fit for a mixture of 1:1, 1:2, and 1:3 complexes (Figures S3 and S4 in the Supporting Information). The stepwise formation constants K_1, K_2, and K_3 estimated by the curve-fit method are summarized in Table 1, and their calculations are detailed in the Experimental Section. When their $\log K_1$ values were compared, un- and monosubstituted tripods **1** and **2** gave larger $\log K_1$ values than diastereomers of disubstituted tripods **3**: for Eu^{3+} complexes, $\log K_1 = 7.5$ for **1**, 7.4 for (*R*)-**2**, 6.9 for (*R*,*R*)-**3**, and 6.7 for (*R*,*S*)-**3**; for Tb^{3+} complexes, $\log K_1 = 8.1$ for **1**, 7.9 for (*R*)-**2**, 7.1 for (*R*,*R*)-**3**, and 7.0 for (*R*,*S*)-**3**. Mazzanti et al. characterized 1:1 complexes between tripod **1** and some lanthanide chlorides.[16] Their X-ray crystallographic studies revealed that four nitrogen atoms effectively coordinated with the lanthanide cation. Although the disubstituted tripods (*R*,*R*)- and (*R*,*S*)-**3** similarly have three pyridine and one tertiary nitrogen atoms as coordination sites, the two introduced CH_3 substituents seemed to cause steric problems around the tertiary nitrogen atom and to weaken its coordination in the 1:1 complexation. In contrast, all the employed tripods **1**−**3** exhibited total formation constants with similar amplitudes, suggesting that the pyridine nitrogen atoms played major roles in the high-order complexation: $\log(K_1K_2K_3)$ values were estimated as 17.8−18.4 for Eu^{3+} complexes and 18.2−19.0 for Tb^{3+} complexes. When the two diastereomers of tripods **3** were compared, they had almost the same $\log K_1 - K_3$ values, and the ligand chirality was confirmed to rarely affect the stability of lanthanide complexes. Therefore, the introduction of CH_3 substituents modestly modified lanthanide complexation behaviors of tris(2-pyridylmethyl)amine derivatives.

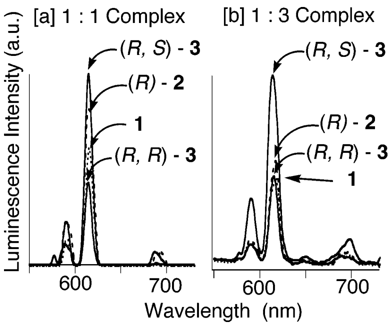


Figure 4. Luminescence spectra of Eu^{3+} complexes with tripods **1**−**3**: (a) $Eu(CF_3SO_3)_3$, 0.0001 mol/L; tripod, 0.0001 mol/L; (b) $Eu(CF_3SO_3)_3$, 0.0001 mol/L; tripod, 0.0003 mol/L in CH_3CN at room temperature. Excitation was at 260 nm.

3. Chirality Effects on Lanthanide Luminescence Behaviors. Lanthanide luminescence is a phenomenon very sensitive to the local environments around the lanthanide center.[18] Since the ligand chirality may alter geometry of the coordinating ligand, symmetry of the ligand field, and related coordination environments, the stereoisomers of tris(2-pyridylmethyl)amine derivatives are expected to provide unique "chirality effects" on the lanthanide luminescence behaviors. When the Eu^{3+} complexes with these tripods were excited at 260 nm, characteristic luminescence bands were recorded at 580, 590, 614, and 698 nm via the ligand-to-metal energy transfer mechanism.[19] Figure 4 illustrates luminescence spectra obtained with 1:1 and 1:3 mixtures of Eu^{3+} cation and tripods, the concentrations of which were finely adjusted to give the same absorbance value at 260 nm. The observed luminescence profiles were interestingly dependent on both ligand chirality and complex stoichiometry. When Eu^{3+} cation and tripod (*R*,*S*)-**3** were typically mixed at 1:3 mole ratio for luminescence measurement, 1:3 complex formed predominantly (see Table 1). Complex composition % based on Eu^{3+} cation concentration: 1:3 complex (87%) ≫ 1:2 complex (11%) ≫ 1:1 complex (2%). Although minor components were not excluded, the disubstituted tripod *(R*,*S)*-**3** exhibited more intense luminescence signals than its diastereomer (*R*,*R*)-**3** and other tripods **1** and (*R*)-**2**. The relative emission intensity at 614 nm was estimated to be 2.2 for (*R*,*S*)-**3**/**1**, 1.1 for (*R*,*R*)-**3**/**1**, and 1.0 for (*R*)-**2**/**1** (Figure 4b). The chirality of tripod had a strong

---

(17) Yamada, T.; Shinoda, S.; Tsukube, H. *Chem. Commun.* **2002**, 1218−1219.

(18) (a) Foster, D. R.; Richardson, F. S. *Inorg. Chem.* **1983**, *22*, 3996−4402. (b) Yanagida, S.; Hasegawa, Y.; Murakoshi, K.; Wada, Y.; Nakashima, N.; Yamanaka, T. *Coord. Chem. Rev.* **1998**, *171*, 461−480. (c) Dickins, R. S.; Aime, S.; Batsanov, A. S.; Beeby, A.; Botta, M.; Bruce, J. I.; Howard, A. K.; Love, C. S.; Parker, D.; Peacock, R. D.; Puschmann, H. *J. Am. Chem. Soc.* **2002**, *124*, 12697−12705. (d) Dickins, R. S.; Parker, D.; Bruce, J. I.; Tozer, D. J. *J. Chem. Soc., Dalton Trans.* **2003**, 1264−1271.

(19) Review on lanthanide luminescence: (a) Buono-Core, G. E.; Li, H. *Coord. Chem. Rev.* **1990**, *99*, 55−87. Recent examples: (b) Werts, M. H. V.; Duin, M. A.; Hofstraat, J. W.; Verhoeven, J. W. *Chem. Commun.* **1999**, 799−800. (c) Taki, M.; Murakami, H.; Sisido, M. *Chem. Commun.* **2000**, 1199−1200. (d) Montalti, M.; Prodi, L.; Zaccheroni, N.; Charbonniere, L.; Douce, L.; Ziessel, R. *J. Am. Chem. Soc.* **2001**, 12694−12695.

effect on the luminescence intensity: 2.0 for (*R*,*S*)-**3**/(*R*,*R*)-**3**. As well-known, the relative intensity of the emission band at 614 nm to that at 590 nm is a sensitive indication of the complex symmetry and also the nature of ligand field.[18,20] Tripod (*R*,*S*)-**3** offered smaller relative intensity (2.6) than those (ca. 4.3) with other tripods. Such differences could be related to the different coordination environments of these complexes.[21] The 1:3 Tb^{3+} complexes with these diastereomers offered signals for $-N-CH(CH_3)-Py$ carbons at different positions in ^{13}C NMR spectra: 60.6 ppm for (*R*,*R*)-**3** and 61.4 ppm for (*R*,*S*)-**3** in CD_3CN. Since other signals for $-N-CH_2-Py$, pyridine ring, and $-CH_3$ carbons were observed at similar positions, the Tb^{3+} complexes with tripod diastereomers were believed to have different steric circumstances around the central tertiary nitrogen atoms. The direct excitation of the Eu^{3+} cation at 394 nm was performed in the presence of 3 equiv of tripods. Since tripod (*R*,*S*)-**3** gave 1.7 times more intense emission at 614 nm than the other three ligands **1**, (*R*)-**2**, and (*R*,*R*)-**3**, the two diastereomers of tripods **3** were confirmed to behave differently in the lanthanide emitting process. The chirality-dependent luminescence was also recorded with 1:1 mixtures of Eu^{3+} and tripod **3** (see Figure 4a): 2.3 for (*R*,*S*)-**3**/(*R*,*R*)-**3**. Therefore, these diastereomers are believed to encapsulate the excited lanthanide center in different fashions.

The Tb^{3+} complexes with tris(2-pyridylmethyl)amine ligands showed intense luminescence bands at 487, 543, 585, and 620 nm in CH_3CN solutions. There are remarkably large chirality effects on the terbium luminescence intensities between disubstituted tripods (*R*,*S*)- and (*R*,*R*)-**3**. When 1:3 complexes were excited at 260 nm, the relative luminescence intensity at 543 nm was estimated to be 4.3 for (*R*,*S*)-**3**/**1**, 1.6 for (*R*)-**2**/**1**, and 1.5 for (*R*,*R*)-**3**/**1**. The two diastereomeric ligands caused a marked difference in luminescence intensity, which was large enough to be recognized by the naked eye (see the Table of Contents Synopsis). Such luminescence phenomena have considerable importance for the rapid screening of chiral substrates.[22] Although several organic receptors have been developed for chirality sensing of organic substrates,[23] the present result provides a new possibility that the designed lanthanide complexes can visually sense the chirality of the coordinative substrates. Table 2 lists the luminescence lifetimes of 1:3 lanthanide complexes. They showed trends similar to those of relative luminescence intensities: for europium luminescence, 1.7 ms for (*R*,*S*)-**3**, 1.5 ms for (*R*)-**2** and **1**, and 1.4 ms for (*R*,*R*)-**3**; for terbium luminescence, 2.3 ms for (*R*,*S*)-**3**, 1.7 ms for (*R*)-**2**, and 1.6 ms for **1** and (*R*,*R*)-**3**. Although tripod (*R*,*S*)-**3** offered a slightly longer lifetime of terbium luminescence than its diastereomer (*R*,*R*)-**3**, the enhanced luminescence phenomenon was remarkable. Probably, the chirality-dependent terbium luminescence can be considered the consequence of several different processes. The lanthanide luminescence phenomena are generally composed of excitation of ligand chromophore, energy transfer from excited chromophore to lanthanide center, nonradiative quenching of the excited lanthanide, and luminescence emittance. Several methods have already been used to enhance the lanthanide luminescence efficiency:[18,19] (1) introduction of intense chromophoric ligand; (2) effective encapsulation of lanthanide center; (3) addition of an external stimulus such as coordinative anions. The results described above emphasize the significance of ligand chirality in the lanthanide luminescence process. Since there are many methodologies to synthesize stereocontrolled ligands, a new series of lanthanide and other metal complexes having intelligent functions can be developed using the designed ligands.

Table 2. Luminescence Profiles of 1:3 Complexes between Tris(2-pyridylmethyl)amine Ligands and Lanthanide Cations (Eu^{3+} and Tb^{3+})

	1	(*R*)-**2**	(*R*,*R*)-**3**	(*R*,*S*)-**3**
“Eu^{3+} 1:3 Complexes”				
log $K_1K_2K_3$	18.0	18.4	17.8	17.9
luminescence intensity	1.0	1.0	1.1	2.2
luminescence lifetime (ms)	1.5	1.5	1.4	1.7
“Tb^{3+} 1:3 Complexes”				
log $K_1K_2K_3$	18.9	19.0	18.2	18.9
luminescence intensity	1.0	1.6	1.5	4.3
luminescence lifetime (ms)	1.6	1.7	1.6	2.3

Experimental Section

General Methods. ^1H and ^{13}C NMR spectra were recorded on JEOL LA-300 and -400 spectrometers. Luminescence spectra were obtained on a Perkin-Elmer LS-50B equipped with a Hamamatsu R-928 photomultiplier, and CD spectra and $[\alpha]^{20}_D$ values were recorded with a Jasco J-720 spectrometer and a Jasco DIP-370 polarimeter, respectively.

Synthesis of Tris(2-pyridylmethyl)amine Ligands. All the employed ligands **1**, (*R*)-**2**, (*R*,*R*)-**3**, and (*R*,*S*)-**3** were prepared as illustrated in Figure 2. Selected data for newly prepared tripods (*R*,*R*)-**3** and (*R*,*S*)-**3** are described below.

(*R*,*S*)-**3**: colorless crystals (from hexane), mp 91−92 °C; >95% de; $[\alpha]^{20}_D$ $-4°$ ($c = 0.52$, $CHCl_3$); $R_f = 0.54$ (5% EtOAc in CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$) δ 8.53 (2H, dq, $J = 4.9$, 1.0 Hz), 8.43 (1H, dq, $J = 4.9$, 1.0 Hz), 7.65 (2H, td, $J = 7.8$, 2.0 Hz), 7.58−7.53 (3H, m), 7.42 (1H, d, $J = 7.8$ Hz), 7.15−7.04 (3H, m), 4.20 (2H, q, $J = 6.8$ Hz), 4.02 (2H,s), 1.27 (6H, d, $J = 6.8$ Hz). Anal. Calcd for $C_{20}H_{22}N_4$: C, 75.44; H, 6.96; N, 17.60. Found: C, 75.56; H, 6.98; N, 17.60.

(*R*,*R*)-**3**: yellow oil (GPC; JAIGEL-1H, 2H; $CHCl_3$), >95% de; $[\alpha]^{20}_D$ $+108°$ ($c = 1.05$, $CHCl_3$); $R_f = 0.53$ (5% EtOAc in CH_2Cl_2); ^1H NMR (400 MHz, $CDCl_3$: see Figure S5 in the Supporting Information) δ 8.52 (2H, dq, $J = 4.9$, 1.0 Hz), 8.42 (1H, dq, $J =$

---

[20] (a) Frey, S. T.; Dew. Horrocks, W. *Inorg. Chim. Acta* **1995**, *229*, 383−390. (b) Parker, D.; Williams, J. A. G. *J. Chem. Soc., Dalton Trans.* **1996**, 3629−3637.

[21] When the europium emission spectra were recorded with narrow emission slits (2.5 nm), the bands observed at 590 nm split: two major components for (*R*,*S*)-**3**; three ones for (*R*,*R*)-**3**. In contrast, the band recorded at 580 nm was very weak and not resolved in each complex.

[22] (a) Hirose, K.; Ogasahara, K.; Nishioka, K.; Tobe, Y.; Naemura, K. *J. Chem. Soc., Parkin Trans.* **2000**, *2*, 1984−1993. (b) Miyaji, H.; Sato, W.; Sessler, J. L. *Angew. Chem., Int. Ed.* **2000**, *39*, 1777−1780. (c) Lee, D. H.; Lee, K. H.; Hong, J.-I. *Org. Lett.* **2001**, *3*, 5−8. (d) Tsubaki, K.; Kusumoto, T.; Hayashi, N.; Nuruzzaman, M.; Fuji, K. *Org. Lett.* **2002**, *4*, 2313−2316.

[23] Several organic fluorescent receptors for chirality sensing of biological substrates were reported: (a) James, T. D.; Sandanayake, K. R. A. S.; Shinkai, S. *Nature* **1995**, *374*, 345−347. (b) Reetz, M. T.; Zonta, A.; Schimossek, K.; Liebeton, K.; Jeager, K.-E. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2830−2832. (c) Wang, D.; Liu, T.-J.; Zhang, W.-C.; Slaven, W. T., IV; Li, C.-J. *Chem. Commun.* **1998**, 1747−1748. (d) Delden, R. A.; Feringa, B. L. *Angew. Chem., Int. Ed.* **2001**, *40*, 3198−3200.

4.9, 1.0 Hz), 7.67−7.52 (4H, m), 7.30 (2H, d, $J = 8.0$ Hz), 7.15−7.00 (3H, m), 4.36 (1H, d, $J_{gem} = 16.6$ Hz), 4.13 (2H, q, $J = 6.8$ Hz), 3.83 (1H, d, $J_{gem} = 16.4$ Hz), 1.43 (6H, d, $J = 6.8$ Hz); ^{13}C NMR (400 MHz, $CDCl_3$: see Figure S6 in the Supporting Information) δ 163.4, 163.3, 148.7, 148.5, 136.1, 122.8, 122.3, 121.7, 121.2, 60.4, 52.8 and 17.8. HRMS: calcd for $C_{20}H_{23}N_4$, M + H$^+$ = *m*/*z* 319.1922; found, *m*/*z* 319.1920.

Tripod (*R*,*S*)-**3** was also characterized by X-ray crystal structure determination (Figure S1 and crystallographic CIF data in the Supporting Information).

Luminescence Experiments. The luminescence experiments were carried out in CH_3CN using two excitation methods. The initial concentrations of lanthanide triflates and tripodal ligands are shown in each figure. Because the lanthanide complexation offered slight UV spectral changes (see Figure S3), the ligand-excitation luminescence spectra were recorded upon excitation at 260 nm, after the concentrations of the complex solutions were finely adjusted to give the same absorbance at 260 nm. The direct excitation of the europium center (at 394 nm) required much higher concentrations of europium complexes than those of the ligand excitation experiments:[24] [tripod] = 1.5×10^{-2} mol/L, [$Eu(CF_3SO_3)_3$] = 5.0×10^{-3} mol/L. The pictures in the Table of Contents Synopsis were taken under the following conditions: [tripod] = 1.5×10^{-3} mol/L; [$Tb(CF_3SO_3)_3$] = 5.0×10^{-4} mol/L in CH_3CN. Its excitation was done using UV lamp for TLC detection.

The lifetimes (τ) are the average values of at least 3 separate measurements, each of which was made by monitoring the emission intensity at 614 (for Eu^{3+}) or 543 nm (for Tb^{3+}) after 20 different delay times spanning a range of at least two lifetimes ($\lambda_{ex} = 260$ nm). Slit widths of 10 nm were used, and the gate time was 0.1 ms. The decay curves were fitted by an equation of the form $I(t) = I(0)\exp(-t/\tau)$ using a curve-fitting program. A high correlation coefficient was observed in each case.

Titration Experiments. For UV titration experiments, we prepared more than 15 samples with different ratios of tripodal ligands to lanthanide triflates. To 2.00 mL of a 1.00×10^{-4} mol/L CH_3CN solution of tripod, we added small amounts of CH_3CN solution containing 1.80×10^{-3} mol/L of lanthanide triflate and 1.00×10^{-4} mol/L of tripod. The UV spectra of the resulting solutions were recorded after 5 min of stirring at room temperature. Their absorbance values at 260 and 269 nm were plotted against mole ratios of ligand/metal to calculate the stepwise log K_i values. Two or three independent experiments were conducted for each combination, and the calculations were carried out as described below using IGOR Pro (version 4, WaveMetrics Inc.). The standard deviations of the estimated log K_i values are shown in Table 1.

Determination of Stepwise Formation Constants. The stepwise formation constants for 1:1, 1:2, and 1:3 (metal:ligand) complexes are given by eqs 1−3 described in the text. The total concentration of ligand L_t was kept constant (1.0×10^{-4} mol/L) during titration experiments, and the total concentration of metal ion M_t increased. The absorbance at 260 or 269 nm was plotted against the molar ratio *x*, M_t/L_t. The absorbance changes at the region where *x* is between 0 and 5 were well reproduced by assuming three different stoichiometries, ML_n (n = 1, 2, and 3). The total concentrations of ligand and metal ion are expressed as

$$M_t = [M] + [ML] + [ML_2] + [ML_3] \tag{4}$$

$$L_t = [L] + [ML] + 2[ML_2] + 3[ML_3] \tag{5}$$

From eqs 1−5, the concentration of free ligand [L] can be obtained by solving the following equation:

$$K_1K_2K_3[L]^4 + (K_1K_2 - K_1K_2K_3L_t + 3K_1K_2K_3L_tx)[L]^3 + (K_1 - K_1K_2L_t + 2K_1K_2L_tx)[L]^2 + (1 - K_1L_t + K_1L_tx)[L] - L_t = 0 \tag{6}$$

The concentration of other species can then be expressed as follows:

$$[M] = \frac{L_tx}{1 + K_1[L] + K_1K_2[L]^2 + K_1K_2K_3[L]^3} \tag{7}$$

$$[ML] = K_1[M][L] \tag{8}$$

$$[ML_2] = K_1K_2[M][L]^2 \tag{9}$$

$$[ML_3] = K_1K_2K_3[M][L]^3 \tag{10}$$

The absorbance of the measured sample in a 1 cm quartz cell can be expressed as

$$\text{abs} = \epsilon_{ML}[ML] + \epsilon_{ML_2}[ML_2] + \epsilon_{ML_3}[ML_3] + \epsilon_M[M] + \epsilon_L[L] \tag{11}$$

where ϵ_X is the molar absorption coefficient (in L·mol^{-1}·cm^{-1}) of the species X. To fit the titration curve, we treated the following values as variables to be determined, K_1, K_2, K_3, ϵ_{ML}, ϵ_{ML_2}, and ϵ_{ML_3}, while ϵ_M and ϵ_L were experimentally determined and used as constants.

Acknowledgment. This work was supported by Grant-in-Aids for Scientific Research (No. 13874077) from the Japan Society for the Promotion of Science, the Development of Innovative Nuclear Technologies in 2002 from the Ministry of Education, Culture, Sports, Science, and Technology of Japan, and also Reimei Research in 2001 from the Japan Atomic Energy Research Institute. The authors are grateful to Professors Kiyoshi Isobe, Isamu Kinoshita, and Makoto Tadokoro of Osaka City University for valuable comments on CD and X-ray measurements and to Professor Kiyoshi Matsumoto of Kyoto University for valuable suggestions on high-pressure ligand synthesis. They also thank Professor James P. Riehl and Dr. Gilles Muller of the University of Minnesota−Duluth for their kind measurements of circularly polarized luminescence spectra.

Supporting Information Available: Figures showing the crystal structure of tripod (*R*,*S*)-**3**, ESI-MS spectra of tripod (*R*,*R*)-**3** and Tb(triflate)$_3$ in CH_3CN, titration curves of tripod−Ln^{3+} (Tb^{3+} or Eu^{3+}) complexes, and ^{1}H and ^{13}C NMR spectra of tripod (*R*,*R*)-**3** and crystallographic data in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

IC020726R

---

[24] Woods, M.; Aime, S.; Botta, M.; Howard, J. A. K.; Moloney, J. M.; Navet, M.; Parker, D.; Port, M.; Rousseaux, O. *J. Am. Chem. Soc.* **2000**, *122*, 9781−9792.