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Synthesis of Asymmetric Bridging Ligand, *trans*–1,4–bis(1,10–phenanthrolin–4–yl)–1–butene

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Abstract

Efficient synthesis of an asymmetric bridging ligand **1**, *trans*–1,4–bis(1,10–phenanthrolin–4–yl)–1–butene, was reported by the use of 8–aminoquinoline as a starting material. The structures of the target compound and the major intermediates were assigned by ^{1}H NMR and ES–Mass spectra.

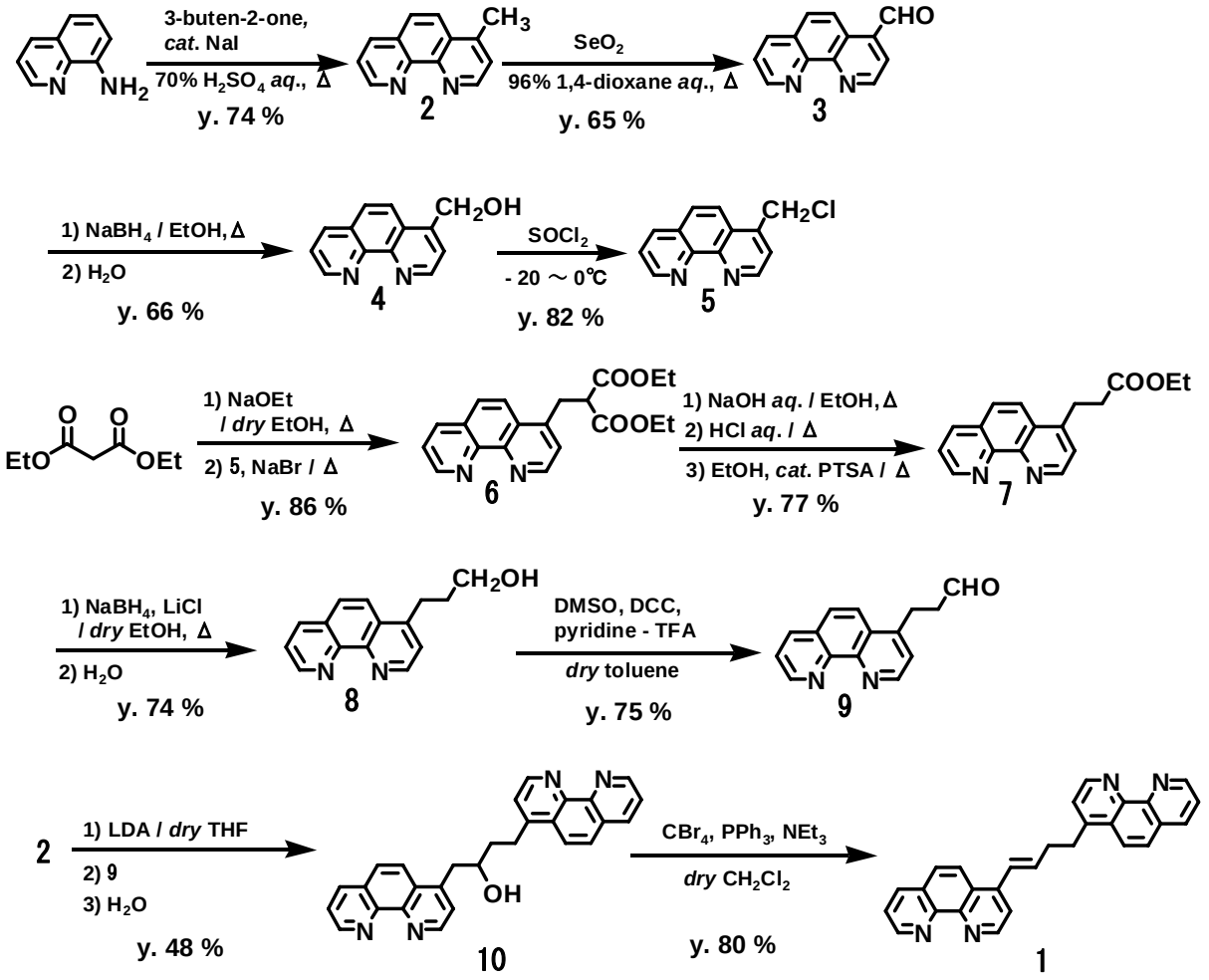
Introduction

The organic heteronuclear polymetallic complexes have been expected for multifunctional molecules through combination of different functions as reaction catalysts and chemical devices due to their multifunctions, which mononuclear complexes cannot afford. In fact, recently, photochemical and electrochemical properties of many kinds of heteronuclear complexes have been studied by many research groups.[1–4] The controlling factors of these properties are the types of central metals, the structures of the peripheral ligands, the bridging ligands, and so on.[1–4] These ligands are known to largely affect the efficiency or lifetime of electron or energy transfer by controlling the redox potentials.[4,5] Nevertheless, there are a few researches which focus on the structures and the effects of bridging ligands.[1,3,6–8]

Most bridging ligands studied so far are limited to those which have simple methylene[6,7] or phenylene spacers[3] and are fully conjugated by aromatic rings[1] or multiple bonds.[8] All of these bridging ligands have symmetric spacers. Therefore, it is interesting to investigate the effects of an asymmetric spacer on the chemical and electrochemical properties of heteronuclear complexes. We report here the first synthesis of a new bridging ligand, *trans*–1,4–bis(1,10–phenanthrolin–4–yl)–1–butene **1**, having an asymmetric spacer with a double bond.

Results

The synthetic route of the bridging ligand **1** is summarized in Scheme 1. All compounds were characterized by ^{1}H NMR and ES–Mass spectroscopies.



Scheme 1

The compounds **2**–**4** were prepared starting from 8–aminoquinoline according to the reported methods.[9,10)]

The chloride **5** was prepared by the reaction of **4** and excess $SOCl_2$ at –20 ℃. The reactions at higher temperatures, under refluxing condition and at rt, led to a complicated mixture. In bromination of **4** by 48% HBr *aq.*, no bromide was obtained after purification by column chromatography although the bromide had been detected in the reaction mixture by TLC tracing.

The diester **6** was prepared as follows: After deprotonation of ethyl malonate with sodium ethoxide, the generated carbanion was alkylated by **5** in the presence of excess NaBr as a halogen exchange reagent. After purification by alumina column chromatography, pure **6** was obtained in high yield.

The alcohol **8** was obtained in high yield by the use of $NaBH_4$ and lithium chloride in *dry* EtOH. On the other hand, the use of $LiAlH_4$ and $LiBH_4$ led to low yields due to reduction of aromatic rings. In fact, the ^1H NMR spectrum of the by–product showed some peaks, which had been assigned to aromatic protons of **7**, disappeared.

The aldehyde **9** was prepared by oxidation of **8** through the reaction with DMSO and dicyclohexylcarbodiimide under mild conditions. It is important to purify the crude product rapidly to obtain pure **9** in good yield. An attempt to oxidize **8** in the presence of pyridinium dichromate failed due to decomposition of aromatic rings.

The target bridging ligand **1** was efficiently synthesized by the bromination of **10** by the use of CBr_4 and PPh_3, followed by selective dehydrobromination with triethylamine. The regioselectivity of the reaction was confirmed by the vicinal coupling constant between the olefinic protons (J = 15.8 Hz) observed in the ^{1}H NMR spectrum.[11)]

Conclusion

We have investigated a synthetic method of a new bridging ligand, *trans*–1,4–bis(1,10–phenanthrolin–4–yl)–1–butene **1**, having an asymmetric spacer. As a result, an efficient synthetic route of **1** was established through coupling of 1,10–phenanthroline derivatives and halogenation/regioselective dehydrohalogenation. Application of the present bridging ligand to heteronuclear complexes is under way.

Experimental

All ^{1}H NMR spectra were measured at 300 MHz on a Bruker AC–300P spectrometer, using tetramethylsilane (TMS) as an internal standard. (Molecular Analysis and Life Science Center, Saitama University) Electrospray mass spectra were recorded with an Applied Biosystems Mariner spectrometer. (MALS, Saitama University)

All reagents and solvents that were commercially available were purchased from Kanto Chemical Co., Inc., Wako Pure Chemical Industries, Ltd., Tokyo Chemical Industry Co., Ltd., or Sigma–Aldrich Co. at the highest quality and were purified by distillation when necessary.

4–Methyl–1,10–phenanthroline (**2**), 1,10–phenanthroline–4–carbaldehyde (**3**), and 4–(hydroxymethyl)–1,10–phenanthroline (**4**) were prepared according to the literatures.[9,10)]

4–(Chloromethyl)–1,10–phenanthroline (5). Under nitrogen atmosphere, **4** (1.04 g, 4.96 mmol) was added to $SOCl_2$ (10 ml) at –20 ℃, and the temperature was gradually raised to *ca.* 0 ℃ for 5 h. After the reaction, ice water was added to decompose remaining $SOCl_2$ until the evolution of SO_2 stopped. The solution was basified to pH 9 with *sat.* Na_2CO_3 *aq.*, extracted with chloroform, washed with *sat.* NaCl *aq.*, dried with anhydrous Na_2SO_4 and concentrated. The residue was purified by neutral alumina column chromatography with chloroform/hexane /methanol (v/v/v, 100/100/1) to obtain a white solid (933 mg, 4.08 mmol, 82%).

^{1}H NMR ($CDCl_3$): δ = 9.22 (*dd*, 1H, J = 4.3, 1,7 Hz, ArH), 9.18 (*d*, 1H, J = 4.6 Hz, ArH), 8.27 (*dd*, 1H, J = 7.3, 1.7 Hz, ArH), 8.10 (*d*, 1H, J = 9.0 Hz, ArH), 7.90 (*d*, 1H, J = 9.0 Hz, ArH), 7.67 (*d*, 1H, J = 4.6 Hz, ArH), 7.66 (*dd*, 1H, J = 7.3, 4.3 Hz, ArH), 5.06 (*s*, 2H, ArCH_2Cl). ES–MS: 230 $[M+H]^+$

2–(1,10–Phenanthrolin–4–ylmethyl)malonic acid diethyl ester (6). Under nitrogen atmosphere, Na (215 mg, 9.34 mmol) was added to *dry* EtOH (10 ml) and stirring was continued until all Na dissolved at rt. Ethyl malonate (1.9 ml, 12.5 mmol) was added to the solution and refluxed for 1.5 h. The solution of **5** (1.51 g, 6.58 mmol) in *dry* EtOH (15

ml) and NaBr (1.44 g, 14.0 mmol) were added to the NaOEt/EtOH solution, and the mixture was refluxed overnight. After removing ethanol, water was added and extracted with chloroform, and the extract was dried with anhydrous Na_2SO_4 and concentrated. The residue was purified by neutral alumina column chromatography with chloroform/hexane (v/v, 1/1) to obtain a pale yellow oil (1.99 g, 5.65 mmol, 86 %).
^{1}H NMR ($CDCl_3$): δ = 9.22 (*dd*, 1H, J = 4.3, 1,7 Hz, ArH), 9.07 (*d*, 1H, J = 4.4 Hz, ArH), 8.24 (*dd*, 1H, J = 8.1, 1.7 Hz, ArH), 8.06 (*d*, 1H, J = 9.2 Hz, ArH), 7.84 (*d*, 1H, J = 9.2 Hz, ArH), 7.63 (*dd*, 1H, J = 8.1, 4.3 Hz, ArH), 7.50 (*d*, 1H, J = 4.4 Hz, ArH), 4.18 (*m*, 4H, $ArCH_2CH(COOCH_2CH_3)_2$), 3.80 (*m*, 3H, $ArCH_2CH(COOCH_2CH_3)_2$), 1.18 (*t*, 6H, J = 7.2 Hz, $ArCH_2CH(COOCH_2CH_3)_2$). ES–MS: 354 $[M+H]^+$

3–(1,10–Phenanthrolin–4–yl)propionic acid ethyl ester (7). To the solution of **6** (1.99 g, 5.65 mmol) in EtOH (30 ml) was added 3 M NaOH *aq.* (10 ml) and the resulting mixture was refluxed for 5 h. After removing ethanol, the solution was acidified to pH 1 with 3 M HCl *aq.* After refluxing overnight, the solution was concentrated. A catalytic amount of PTSA (*p*–toluenesulfonic acid) (58.5 mg, 0.34 mmol) was added to the EtOH (40 ml) solution of the residue and the mixture was refluxed overnight. The solution was concentrated, weakly basified with *sat.* $NaHCO_3$ *aq.*, and extracted with chloroform. The organic layer was dried with anhydrous Na_2SO_4 and concentrated. The residue was purified by neutral alumina column chromatography with chloroform/hexane (v/v, 1/1) to obtain a white solid (1.12 g, 4.35 mmol, 77 %).
^{1}H NMR ($CDCl_3$): δ = 9.20 (*dd*, 1H, J = 4.1, 1,8 Hz, ArH), 9.10 (*d*, 1H, J = 4.6 Hz, ArH), 8.26 (*dd*, 1H, J = 8.1, 1.8 Hz, ArH), 8.06 (*d*, 1H, J = 9.2 Hz, ArH), 7.84 (*d*, 1H, J = 9.2 Hz, ArH), 7.64 (*dd*, 1H, J = 8.1, 4.1 Hz, ArH), 7.50 (*d*, 1H, J = 4.6 Hz, ArH), 4.16 (*q*, 2H, J = 7.1 Hz, $ArCH_2CH_2COOCH_2CH_3$), 3.50 (*t*, 2H, J = 7.9 Hz, $ArCH_2CH_2COOCH_2CH_3$), 2.82 (*t*, 2H, J = 7.9 Hz, $ArCH_2CH_2COOCH_2CH_3$), 1.23 (*t*, 3H, J = 7.1 Hz, $ArCH_2CH_2COOCH_2CH_3$). ES–MS: 281 $[M+H]^+$

4–(3–Hydroxypropyl)–1,10–phenanthroline (8). Under nitrogen atmosphere, $NaBH_4$ (94.1 mg, 2.49 mmol) and LiCl (106 mg, 2.49 mmol) were added to the solution of **7** (698 mg, 2.49 mmol) in *dry* EtOH (20 ml), and refluxed for 10 h. During this period, the same amount of $NaBH_4$ and LiCl were added in every few hours. After 10 h, the reaction was quenched with water. After removing ethanol, the aqueous layer was extracted with chloroform, and dried with anhydrous Na_2SO_4 and concentrated. The residue was purified by neutral alumina column chromatography with chloroform/hexane (v/v, 2/1) to obtain a white solid (437 mg, 1.83 mmol, 74 %).
^{1}H NMR ($CDCl_3$): δ = 9.14 (*dd*, 1H, J = 4.3, 1,8 Hz, ArH), 9.00 (*d*, 1H, J = 4.6 Hz, ArH), 8.18 (*dd*, 1H, J = 8.1, 1.8 Hz, ArH), 8.01 (*d*, 1H, J = 9.2 Hz, ArH), 7.71 (*d*, 1H, J = 9.2 Hz, ArH), 7.58 (*dd*, 1H, J = 8.1, 4.3 Hz, ArH), 7.42 (*d*, 1H, J = 4.6 Hz, ArH), 3.79 (*t*, 2H, J = 6.2 Hz, $ArCH_2CH_2CH_2OH$), 3.22 (*t*, 2H, J = 7.7 Hz, $ArCH_2CH_2CH_2OH$), 2.03 (*m*, 2H, $ArCH_2CH_2CH_2OH$). ES–MS: 239 $[M+H]^+$

3–(1,10–Phenanthrolin–4–yl)propanal (9).[12] Under nitrogen atmosphere, **8** (508 mg, 2.13 mmol) was dissolved in a mixture of anhydrous DMSO (8.0 ml) and toluene (8.0 ml) containing dicyclohexylcarbodiimide (DCC) (1.30 g, 6.30 mmol) and pyridine (170 μl, 2.10 mmol). Trifluoroacetic acid (85 μl, 1.05 mmol) was then added, and the mixture was stirred for 2.5 h at rt. Oxalic acid (570 mg, 6.30 mmol) was added to destroy excess DCC and after 30 min, chloroform (25 ml) and water (25 ml) were added and dicyclohexylurea was removed by filtration. The aqueous layer was basified to pH 9 with *sat.* Na_2CO_3 *aq.*, and extracted with chloroform. The organic layer was washed with water, dried with anhydrous Na_2SO_4, and concentrated. The residue was purified by neutral alumina column chromatography with chloroform/hexane (v/v, 3/1) to obtain a white solid (379 mg, 1.60 mmol, 75 %).
^{1}H NMR ($CDCl_3$): δ = 9.92 (*s*, 1H, $ArCH_2CH_2CHO$), 9.20 (*dd*, 1H, *J* = 4.3, 1.8 Hz, ArH), 9.09 (*d*, 1H, *J* = 4.4 Hz, ArH), 8.26 (*dd*, 1H, *J* = 8.0, 1.8 Hz, ArH), 8.01 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.85 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.64 (*dd*, 1H, *J* = 8.0, 4.3 Hz, ArH), 7.48 (*d*, 1H, *J* = 4.4 Hz, ArH), 3.50 (*t*, 2H, *J* = 7.5 Hz, $ArCH_2CH_2CHO$), 3.01 (*t*, 2H, *J* = 7.5 Hz, $ArCH_2CH_2CHO$). ES–MS: 270 $[M+MeOH+H]^+$

1,4–Bis(1,10–phenanthrolin–4–yl)–2–butanol (10). Under nitrogen atmosphere, 2.0 M lithium diisopropylamide in heptane/tetrahydrofuran/ethylbenzene (215 μl, 0.43 mmol) was added to a *dry* THF (8 ml) solution of **2** (82.2 mg, 0.42 mmol) at –78 ℃, and the temperature was gradually raised to rt for 4 h.[6] To this solution was added a *dry* THF (11 ml) solution of **9** (101 mg, 0.43 mmol) at –41 ℃, and the temperature was gradually raised to rt for 16 h. After quenching with water, all organic solvents were removed and the aqueous layer was extracted with chloroform/methanol. The organic layer was dried with anhydrous Na_2SO_4 and concentrated. The residue was purified by neutral alumina column chromatography with chloroform to obtain a pale orange solid (87.2 mg, 0.20 mmol, 48 %).
^{1}H NMR ($CDCl_3$): δ = 9.19 (*dd*, 1H, *J* = 4.4, 1,9 Hz, ArH), 9.12 (*dd*, 1H, *J* = 4.4, 1,8 Hz, ArH), 9.07 (*d*, 1H, *J* = 4.4 Hz, ArH), 8.98 (*d*, 1H, *J* = 4.4 Hz, ArH), 8.24 (*dd*, 1H, *J* = 8.1, 1.9 Hz, ArH), 8.16 (*dd*, 1H, *J* = 7.9, 1.8 Hz, ArH), 8.10 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.89 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.80 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.66~7.59 (*m*, 3H, ArH), 7.52 (*d*, 1H, *J* = 4.4 Hz, ArH), 7.48 (*d*, 1H, *J* = 4.4 Hz, ArH), 4.27~4.20 (*m*, 1H, $ArCH_2CH(OH)CH_2CH_2Ar$), 3.62~3.52 (*m*, 1H, $ArCH_2CH(OH)CH_2CH_2Ar$), 3.41~3.25 (*m*, 3H, $ArCH_2CH(OH)CH_2CH_2$ Ar) , 2.18 (*m*, 2H, $ArCH_2CH(OH)CH_2CH_2Ar$). ES–MS: 431 $[M+H]^+$, 216 $[M+2H]^{2+}$

***trans*–1,4–Bis(1,10–phenanthrolin–4–yl)–1–butene (1).** To a stirred solution of **10** (40.9 mg, 95.0 μmol) in *dry* CH_2Cl_2 (2 ml) under nitrogen atmosphere was added CBr_4 (62.0 mg, 187 μmol). The mixture was stirred for 10 min at rt, and then a solution of PPh_3 (51.2 mg, 195 μmol) in *dry* CH_2Cl_2 (0.4 ml) was slowly added.[13] Then triethylamine (26.0 μl, 186 μmol) was added to the solution and the mixture was stirred for 3.5 h at rt. The reaction mixture was quenched with water and then diluted with chloroform. The organic layer was separated and washed with *sat.* NaCl *aq.*, dried with

anhydrous Na_2SO_4 and concentrated. The residue was purified by neutral alumina thin layer chromatography with chloroform/methanol (v/v, 50/1) to obtain a pale yellow solid(31.5 mg, 76.4 μmol, 80 %).

^{1}H NMR ($CDCl_3$): δ = 9.22 (*dd*, 1H, *J* = 4.2, 1,7 Hz, ArH), 9.19 (*dd*, 1H, *J* = 4.4, 1,7 Hz, ArH), 9.14 (*d*, 1H, *J* = 4.8 Hz, ArH), 9.10 (*d*, 1H, *J* = 4.6 Hz, ArH), 8.24 (*dd*, 1H, *J* = 7.9, 1.7 Hz, ArH), 8.22 (*dd*, 1H, *J* = 8.1, 1.7 Hz, ArH), 8.11 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.84 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.83 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.71 (*d*, 1H, *J* = 9.2 Hz, ArH), 7.64 (*m*, 2H, ArH), 7.60 (*d*, 1H, *J* = 4.8 Hz, ArH), 7.55 (*d*, 1H, *J* = 4.6 Hz, ArH), 7.11 (*d*, 1H, *J* = 15.8 Hz, ArC*H*CHCH$_2$CH$_2$Ar), 6.56 (*dt*, 1H, *J* = 15.8, 7.0 Hz, ArCHC*H*CH$_2$CH$_2$Ar), 3.47 (*t*, 2H, *J* = 7.4 Hz, ArCHCHCH$_2$C*H*$_2$Ar), 2.94 (*dt*, 2H, *J* = 7.4, 7.0 Hz, ArCHCHC*H*$_2$CH$_2$Ar). ES–MS: 413 $[M+H]^+$, 207 $[M+2H]^{2+}$

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