Journal of Organometallic Chemistry 696 (2011) 2767–2771

Contents lists available at ScienceDirect

Journal of Organometallic Chemistry

journal homepage: www.elsevier.com/locate/jorganchem

Communication

Diiron propanedithiolate complex bearing the pyridyl-functionalized phosphine ligand axially coordinated to a photosensitizer zinc tetraphenylporphyrin

Xu-Feng Liu*, Xun-Wen Xiao

Department of Chemical Engineering, Ningbo University of Technology, Ningbo 315016, China

ARTICLE INFO

Article history:
Received 8 February 2011
Received in revised form
29 April 2011
Accepted 11 May 2011

Keywords:
Diiron propanedithiolate
Zinc tetraphenylporphyrin
Axial coordination
Synthesis
Crystal structure

ABSTRACT

Treatment of the starting material (μ-PDT)$Fe_2(CO)_6$ (PDT = $SCH_2CH_2CH_2S$) with 4-diphenylphosphinoaminopyridine ($PyNHPPh_2$) in the presence of the decarbonylating agent $Me_3NO\cdot 2H_2O$ afforded (μ-PDT)$Fe_2(CO)_5(PyNHPPh_2)$ (**1**) in 56% yield. Further treatment of **1** with Zinc tetraphenylporphyrin (ZnTPP) yielded the target light-driven model compound (μ-PDT)$Fe_2(CO)_5(PyNHPPh_2)$(ZnTPP) (**2**) in 94% yield. The new complexes **1** and **2** were characterized by elemental analysis, NMR, IR, and X-ray crystallography. The molecular structure of **2** revealed its precursor **1** and a photosensitizer ZnTPP joined together through axial coordination. Furthermore, the fluorescence emission spectra and electrochemistry were also investigated.

1. Introduction

In recent years, light-driven model compounds containing a catalytic diiron dithiolate moiety and a photosensitizer unit have been received considerable attention due to their unique structures and novel properties [1–6]. Besides, porphyrin and metalloporphyrin were designed as a photosensitizer in the photoinduced electron transfer system because they have high efficiency in absorbing the energy of sunlight and long lifetime of the excited-state [7]. Some examples for the model compounds containing a [Fe_2S_2] cluster and a photosensitizer porphyrin or metalloporphyrin were shown in Chart 1. Song and co-workers reported a model for the diiron azadithiolate moiety covalently bonded to a porphyrin **A** [8] and afterward, its light-driven hydrogen evolution properties were studied in the presence of electron donor EtSH and proton source CF_3COOH [9]. In addition, another type of model such as **B** [10] and **C** [11] was successfully synthesized and structurally characterized. Very recently, a new model for the diiron propanedithiolate complex with the pyridyl-functionalized phosphine ligand (μ-PDT)$Fe_2(CO)_5[PPh_2(4\text{-}Py)]$ axially coordinated to a metalloporphyrin ZnTPP **D** was obtained *via* self-assembly and its photoinduced hydrogen generation properties were investigated [12]. Based on these previous works, we carried out a study on the reaction of diiron propanedithiolate complex containing a pyridyl-functionalized phosphine ligand with a photosensitizer ZnTPP and have successfully prepared a new light-driven model compound. Herein, we now report our results.

2. Results and discussion

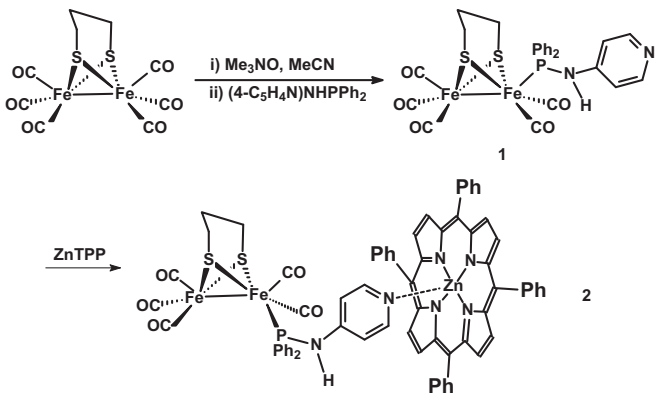
2.1. Synthesis and characterization

The synthetic methods for our target complexes based on the CO substitution reactions with monophosphine ligands [13] (Scheme 1). Treatment of (μ-PDT)$Fe_2(CO)_6$ with 1 equivalent of $Me_3NO\cdot 2H_2O$ in MeCN at room temperature followed by addition of $PyNHPPh_2$ afforded the pyridyl-containing complex **1** in 56% yield. Further treatment of **1** with ZnTPP gave the target model compound **2** in 94% yield.

The new complexes **1** and **2** were characterized by elemental analysis and various spectroscopic techniques. The IR spectra of **1** and **2** displayed three absorption bands in the range of 2042–1948 cm^{-1} for their terminal carbonyls and the $\nu_{C\equiv O}$ values markedly shifted toward lower frequencies relative to parent complex (μ-PDT)$Fe_2(CO)_6$ (2072, 2033, 1993 cm^{-1}) [14] because the $PyNHPPh_2$ is stronger electron-donating ligand than CO [13]. Complex **2** also displayed three absorption bands at 1504, 1484, and 1437 cm^{-1} for the pyrrole rings of ZnTPP [15]. The ^1H NMR spectra of **2** showed two singlets at δ 1.49 and 1.46 ppm for its pyridyl group and the values shifted toward high field relative to the corresponding signals of its precursor **1** due to the strong shielding effect of ZnTPP upon axial coordination [16]. The ^{31}P NMR spectra of **1** and

* Corresponding author. Tel./fax: +86 574 87089989.
E-mail address: nkxfliu@yahoo.com.cn (X.-F. Liu).

0022-328X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jorganchem.2011.05.007



Scheme 1. Synthesis of complexes **1** and **2**.

2 demonstrated a singlet at δ 94.68 and 95.28 ppm, respectively, for their P atom of $PyNHPPh_2$ coordinated to one Fe atom of the diiron subsite [17]. It follows that the ^{31}P NMR value of $PyNHPPh_2$ (19.4 ppm in free $PyNHPPh_2$ [18]) will shift toward lower field upon coordination. In addition, the ^{13}C NMR spectra of **1** and **2** exhibited a doublet at approximately δ 212 ppm for $PFe(CO)_2$ and a singlet at approximately δ 209 ppm for $Fe(CO)_3$ [19].

2.2. X-ray crystal structures of *1* and *2*

The molecular structures of **1** and **2** have been determined by single crystal X-ray diffraction analysis. As shown in Fig. 1, complex **1** contains a butterfly $[Fe_2S_2]$ cluster with five carbonyls and one $PyNHPPh_2$ ligands. A diiron propanedithiolate unit has two fused six-membered rings, in which one six-membered ring C8C7S1Fe2S2C9 has a boat conformation and another six-membered ring C8C7S1Fe1S2C9 adopted a chair conformation. The pyridyl-functionalized phosphine ligand $PyNHPPh_2$ resides in an axial position of the square-pyramidal geometry of the Fe2 atom which is consistent with previously reported corresponding diiron dithiolate complexes with monophosphine ligands such as (μ-PDT)$Fe_2(CO)_5(Ph_2PCH_2COOH)$ [20], (μ-PDT)$Fe_2(CO)_5[Ph_2PNHCH_2CH_2N(CH_3)_2]$ [21], and $[(\mu\text{-}SCH_2)CH(OH)]Fe_2(CO)_5(PPh_3)$ [22]. The Fe1-Fe2 bond length [2.5054(14) Å] is close to its parent complex (μ-PDT)$Fe_2(CO)_6$ [2.5103(11) Å] [14] and analogous diiron dithiolate complexes (μ-PDT)$Fe_2(CO)_5[Ph_2PNHCH_2CH_2N(CH_3)_2]$ [2.5089(8) Å] and (μ-PDT)$Fe_2(CO)_5[Ph_2PNH(2\text{-}NH_2C_6H_4)]$ [2.5010(8) [21], but shorter than those in the structures of natural enzymes *Clostridium pasteurianum* and *Desulfovibrio desulfuricans* (2.55–2.62 Å) [23,24].

As shown in Fig. 2, light-driven model compound **2** contains its precursor **1** and a photosensitizer ZnTPP joined together through axial coordination. The Fe1–Fe2 bond length [2.545(2) Å] of **2** is longer than that of **1** [2.5054(14) Å] due to the coordination effect of metalloporphyrin [12]. It is interesting to find out that the pyridyl-functionalized phosphine ligand $PyNHPPh_2$ in **2** occupies a basal position of the square-pyramidal geometry of the Fe2 atom in order to reduce the steric repulsion between the porphyrin ring and the propylene group. The Zn1–N2 bond length [2.113(7) Å] is in good agreement with the corresponding length in a similar compound [10]. While the dihedral angle between the porphyrin plane and the pyridine plane is 69.5°, the twist angles between the four benzene rings and the porphyrin plane are 82.5°, 112.9°, 121.0°, and 120.1°, respectively. In addition, the porphyrin ring is slightly ruffled with 0.2822 Å out-of-plane displacement of the central zinc because of axial coordination [25].

2.3. Fluorescence emission spectra

The fluorescence emission spectra of ZnTPP without and with complex **1** were studied under the same conditions. As shown in Fig. 3, ZnTPP shows two fluorescence emission bands at 598 and 645 nm. After addition of 20 equiv. of complex **1**, the fluorescence emission bands are red-shifted by 15–16 nm with respect to the corresponding bands of ZnTPP and the intensities are quenched with an efficiency of 75%. This is because the assembly of ZnTPP and complex **1** exists via axial coordination between the pyridine nitrogen atom and zinc atom in ZnTPP [11]. The decreased intensities of the bands of ZnTPP with complex **1** relative to free ZnTPP may be due to the electron transfer from photoexcited ZnTPP to the diiron subsite [10].

2.4. Electrochemistry of complex *1*

The electrochemical properties of complex **1** were studied by cyclic voltammetry. As shown in Fig. 4, complex **1** displayed one

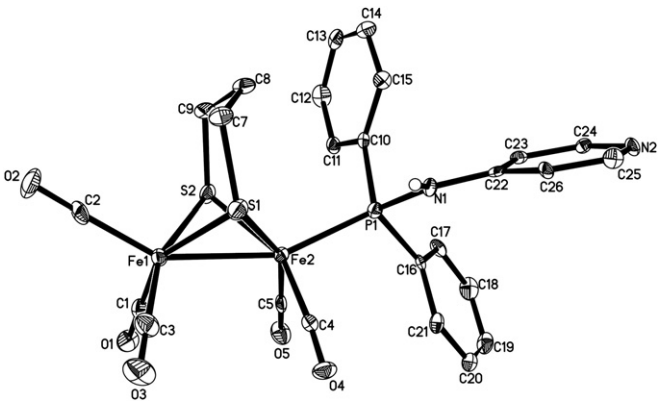


Fig. 1. ORTEP view of **1** with 30% probability level ellipsoids. Selected bond lengths (Å) and bond angles (°): Fe(1)–S(1) 2.2712(19); Fe(1)–S(2) 2.261(2); Fe(1)–Fe(2) 2.5054(14); Fe(2)–P(1) 2.220(2); Fe(2)–S(1) 2.270(2); Fe(2)–S(2) 2.2541(19); P(1)–N(1) 1.702(5); S(2)–Fe(1)–S(1) 84.47(8); S(2)–Fe(1)–Fe(2) 56.16(5); S(1)–Fe(1)–Fe(2) 56.48(6); P(1)–Fe(2)–Fe(1) 156.26(6); S(2)–Fe(2)–Fe(1) 56.43(6); S(1)–Fe(2)–Fe(1) 56.54(6); N(1)–P(1)–Fe(2) 116.3(2); Fe(2)–S(1)–Fe(1) 66.98(6); Fe(2)–S(2)–Fe(1) 67.40(6).

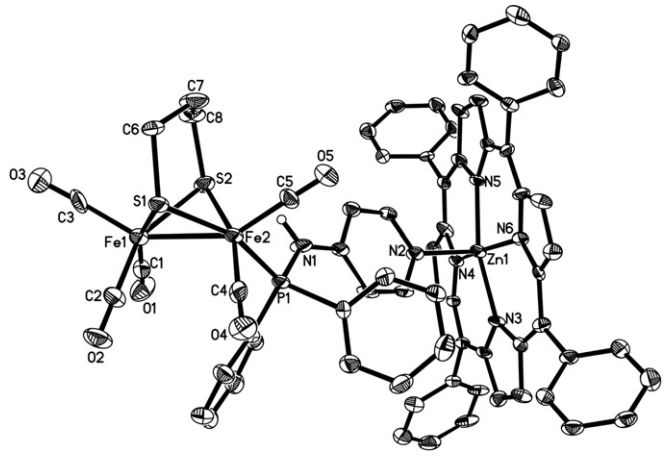


Fig. 2. ORTEP view of **2** with 30% probability level ellipsoids. Selected bond lengths (Å) and bond angles (°): Zn(1)–N(2) 2.113(7); Fe(1)–S(1) 2.250(3); Fe(1)–S(2) 2.245(3); Fe(1)–Fe(2) 2.545(2); Fe(2)–P(1) 2.213(3); Fe(2)–S(1) 2.245(3); Fe(2)–S(2) 2.250(3); P(1)–N(1) 1.708(7); S(2)–Fe(1)–S(1) 84.89(10); S(2)–Fe(1)–Fe(2) 55.59(8); S(1)–Fe(1)–Fe(2) 55.43(8); P(1)–Fe(2)–Fe(1) 105.77(9); S(1)–Fe(2)–Fe(1) 55.60(8); S(2)–Fe(2)–Fe(1) 55.43(8); N(1)–P(1)–Fe(2) 112.2(3); Fe(2)–S(1)–Fe(1) 68.97(9); Fe(1)–S(2)–Fe(2) 68.98(9).

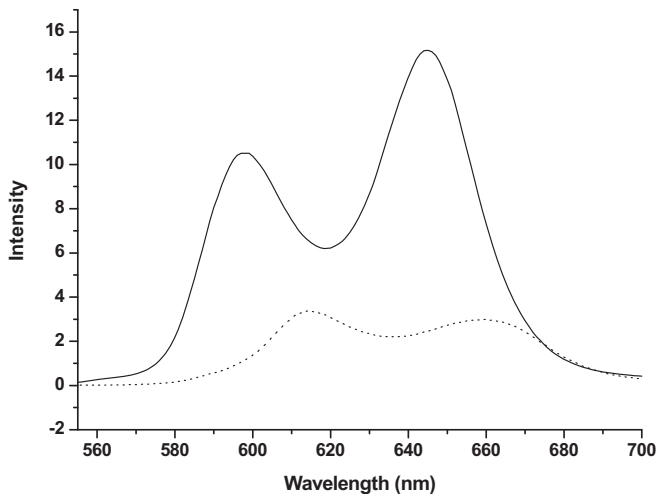


Fig. 3. Fluorescence emission spectra (λ_{ex} = 545 nm) of ZnTPP (5×10^{-5} M) in CH_2Cl_2 without (solid line) and with complex **1** (1×10^{-3} M, dotted line).

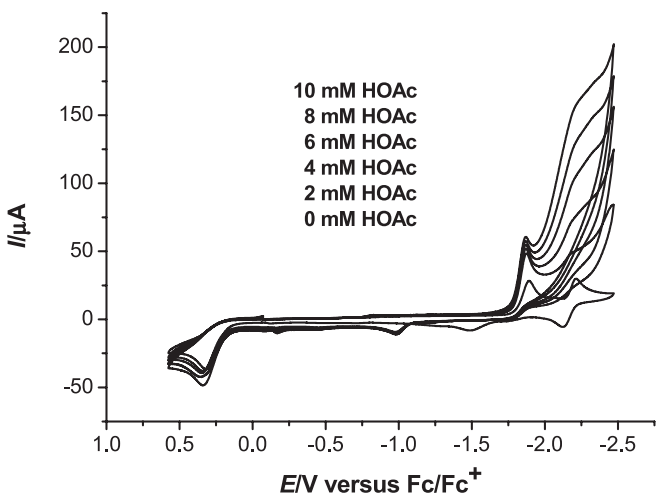


Fig. 4. Cyclic voltammogram of complex **1** (1 mM) in 0.1 M n-Bu_4NPF_6/MeCN with HOAc (0–10 mM) at a scan rate of 100 mV S^{-1}.

irreversible reduction at −1.89 V and one quasi-reversible reduction at −2.21 V, attributed to the Fe^IFe^0 and Fe^0Fe^0 state, respectively [26]. After addition of 2 mM acetic acid, the current intensity at −1.89 V was increased, but did not increase any more with sequential addition of acetic acid. However, the second reduction peak at −2.21 V markedly increases with sequential addition of acetic acid. The sharp increase in its current intensity is typical of an electrochemical catalytic process [27].

3. Conclusions

In summary, we have successfully synthesized a light-driven model compound from a photosensitizer ZnTPP axially coordinated to a diiron propanedithiolate complex bearing the pyridyl-functionalized phosphine ligand. The new complexes **1** and **2** were structurally characterized by various spectroscopic techniques as well as by X-ray crystallography. Further studies of their catalytic properties are in progress in our laboratory.

4. Experimental

4.1. Materials and methods

All reactions were performed using standard Schlenk and vacuum-line techniques under N_2 atmosphere. Acetonitrile was distilled over CaH_2 under N_2. $Me_3NO\cdot 2H_2O$ and other materials were available commercially and used as received. (μ-PDT)$Fe_2(CO)_6$ [14], $PyNHPPh_2$ [18] and ZnTPP [28] were prepared according to literature procedures. IR spectra were recorded on a Nicolet MAGNA 560 FTIR spectrometer. ^1H (^{31}P, ^{13}C) NMR spectra were obtained on a Bruker Avance 500 MHz spectrometer. Elemental analysis was performed by a Perkin–Elmer 240C analyzer. Fluorescence emission spectra were determined on a Hitachi F-4600 fluorescence spectrometer.

4.2. Synthesis of complex (μ-PDT)$Fe_2(CO)_5(PyNHPPh_2)$ (**1**)

To a solution of (μ-PDT)$Fe_2(CO)_6$ (0.386 g, 1 mmol) in CH_3CN (20 mL) was added a solution of $Me_3NO\cdot 2H_2O$ (0.111 g, 1 mmol) in CH_3CN (15 mL). The mixture was stirred at room temperature for 15 min and then (4-C_5H_4N)NH(PPh_2) (0.278 g, 1 mmol) was added. The new mixture was stirred overnight to give a red solution. The solvent was reduced *in vacuo* and the residue was subjected to TLC separation using ethyl acetate/petroleum ether (v/v = 1:1) as eluent. The main red band collection afforded complex **1** as a red

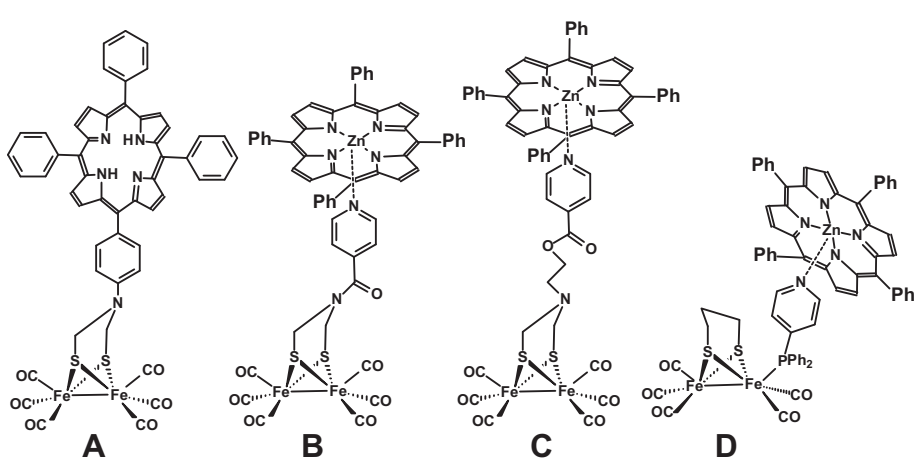


Chart 1. Examples for the model compounds containing a [Fe_2S_2] cluster and a photosensitizer porphyrin or metalloporphyrin.

solid (yield: 0.356 g, 56%). Anal. Calcd for $C_{25}H_{21}Fe_2N_2O_5PS_2$: C, 47.20; H, 3.33; N, 4.40%. Found: C, 47.51; H, 3.52; N, 4.16%. IR (KBr disk): $\nu_{C\equiv O}$ 2041 (vs), 1984 (vs), 1948 (vs) cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ 8.24 (br, 2H, Py-H), 7.77–7.45 (m, 10H, Ar–H), 6.45 (s, 2H, Py-H), 5.78 (d, J_{P-H} = 18.0 Hz, 1H, NH), 2.04–2.00 (m, 2H, $SCH_2CH_2CH_2S$), 1.72–1.62 (m, 4H, $2SCH_2$) ppm. ^{31}P NMR (200 MHz, $CDCl_3$, 85% H_3PO_4): δ 94.68 (s) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ 212.58 (d, J = 13.0 Hz, PFeCO), 209.50 (FeCO), 150.23, 148.96, 148.87, 130.88, 134.64, 134.27, 130.97, 130.69, 130.68, 128.88, 128.80 (Ar–C), 30.23, 22.48 (CH_2) ppm.

4.3. Synthesis of complex (μ-PDT)$Fe_2(CO)_5$(PyNHPPh$_2$)(ZnTPP) (**2**)

A mixture of **1** (0.064 g, 0.1 mmol) and zinc tetraphenylporphyrin (0.068 g, 0.1 mmol) was dissolved in CH_2Cl_2 (3 mL) and then the solution was layed with hexane (5 mL). After 2 days, a purple solid of **2** (0.124 g, 94%) was obtained from filtration and washing with hexane. Anal. Calcd for $C_{69}H_{49}Fe_2N_6O_5PS_2Zn$: C, 63.05; H, 3.76; N, 6.39%. Found: C, 62.77; H, 3.99; N, 6.53%. IR (KBr disk): $\nu_{C\equiv O}$ 2042 (vs), 1985 (vs), 1949 (vs); $\nu_{pyrrole\ ring}$ 1504 (m), 1484 (m), 1437 (m) cm^{-1}. ^1H NMR (500 MHz, $CDCl_3$): δ 8.84 (s, 8H, pyrrole-H), 8.16 (s, 8H, Py and Ar–H), 7.77–7.72 (m, 12H, Ar–H), 7.43–7.33 (m, 10H, Ar–H), 5.53 (br, 1H, NH), 1.93–1.89 (m, 4H, $2SCH_2$), 1.59, 1.49, 1.46 (3s, 6H, Py-H and CH_2) ppm. ^{31}P NMR (200 MHz, $CDCl_3$, 85% H_3PO_4): δ 95.28 (s) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ 212.36 (d, J = 13.2 Hz, PFeCO), 209.33 (FeCO), 149.95, 148.68, 148.59, 146.74, 143.63, 134.52, 134.19, 133.82, 131.48, 130.68, 130.59, 128.75, 128.67, 127.12, 126.22, 120.47, 112.09 (pyrrole-C and Ar–C), 31.60, 30.07 (CH_2) ppm.

4.4. X-ray structure determination

Single crystals of **1** and **2** suitable for X-ray diffraction analysis were grown by slow evaporation of the CH_2Cl_2/hexane solution at 4 °C. A single crystal of **1** or **2** was mounted on a Rigaku MM-007 CCD diffractometer. Data were collected at 113 K by using a graphite monochromator with Mo Kα radiation (λ = 0.71073 Å) in the ω–φ scanning mode. Data collection, reduction and absorption correction were performed by *CRYSTALCLEAR* program [29]. The structure was solved by direct methods using the SHELXS-97 program [30] and refined by full-matrix least-squares techniques (SHELXL-97) [31] on F^2. Hydrogen atoms were located using the geometric method. Details of crystal data, data collections, and structure refinement are summarized in Table 1.

Table 1
Crystal Data and Structure Refinements Details for **1** and **2**.

Complex	**1**	**2**·CH_2Cl_2
Empirical formula	$C_{25}H_{21}Fe_2N_2O_5PS_2$	$C_{70}H_{51}Cl_2Fe_2N_6O_5PS_2Zn$
Formula weight	636.23	1399.23
Temperature (K)	113 (2)	113 (2)
Wavelength (Å)	0.71073	0.71073
Crystal system	Monoclinic	Triclinic
Space group	P2(1)/c	P-1
a (Å)	13.435 (3)	10.972 (2)
b (Å)	17.600 (4)	12.994 (3)
c (Å)	11.101 (2)	23.187 (5)
α (°)	90	85.06 (3)
β (°)	90.07 (3)	85.30 (3)
γ (°)	90	76.17 (3)
V (Å^3)	2624.9 (9)	3191.7 (11)
Z	4	2
D_{calc} (g·cm^{-3})	1.610	1.455
μ (mm^{-1})	1.365	1.052
F(000)	1296	1430
Crystal size (mm^3)	0.20 × 0.18 × 0.12	0.20 × 0.18 × 0.10
θ_{min}, θ_{max} (°)	1.52, 25.02	1.62, 25.02
Reflections collected/unique	20324/4613	23384/11060
R_{int}	0.0893	0.1258
hkl range	$-15 \le h \le 15$	$-13 \le h \le 13$
	$-20 \le k \le 20$	$-15 \le k \le 15$
	$-13 \le l \le 12$	$-27 \le l \le 18$
Completeness to θ_{max} (%)	99.6	98.0
Data/restraints/parameters	4613/98/362	11060/0/803
Goodness of fit on F^2	1.083	1.053
$R1/wR2$ ($I > 2\sigma(I)$)	0.0553/0.1383	0.0966/0.1765
$R1/wR2$ (all data)	0.0916/0.2009	0.1602/0.2068
Largest diff peak and hole/e Å^{-3}	0.831/−0.782	1.699/−1.031

4.5. Electrochemistry

Acetonitrile (HPLC grade) was used for electrochemistry assays. A solution of 0.1 M n-Bu_4NPF_6 in MeCN was used as electrolyte in all cyclic voltammetric experiments. Electrochemical measurements were made using a BAS Epsilon potentiostat. All voltammograms were obtained in a three-electrode cell with a 3 mm diameter glassy carbon working electrode, a platinum counter electrode, and an Ag/Ag^+ (0.01 M $AgNO_3$/0.1 M n-Bu_4NPF_6 in MeCN) reference electrode. The working electrode was polished with 0.05 μm alumina paste and sonicated in water for 10 min prior to use. All potentials are quoted against the ferrocene/ferrocenium (Fc/Fc^+) potential.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (20902051), Foundation of the Education Committee of Zhejiang Province (Z200906833), Ningbo Natural Science Foundation (2010A610186, 2011A610209) and the start-up foundation of Ningbo University of Technology. We thank the Social Practice of the Excellent Engineer Programms of Ningbo University of Technology.

Appendix A. Supplementary material

CCDC 806953 (**1**) and 806952 (**2**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

References

[1] S. Ott, M. Kritikos, B. Åkermark, L. Sun, Angew. Chem. Int. Ed. 42 (2003) 3285.
[2] S. Ott, M. Morgström, M. Kritikos, R. Lomoth, J. Berguist, B. Åkermark, L. Hammarström, L. Sun, Inorg. Chem. 43 (2004) 4683.
[3] J. Ekström, M. Abrahamsson, C. Olson, J. Bergquist, F.B. Kaynak, L. Eriksson, L. Sun, H.-C. Becker, B. Åkermark, L. Hammarström, S. Ott, Dalton Trans. (2006) 4599.
[4] Y. Na, M. Wang, J. Pan, P. Zhang, B. Åkermark, L. Sun, Inorg. Chem. 47 (2008) 2805.
[5] H. Cui, M. Wang, L. Duan, L. Sun, J. Coord. Chem. 61 (2008) 1856.
[6] M. Wang, Y. Na, M. Gorlov, L. Sun, Dalton Trans. (2009) 6458.
[7] I. Okura, Coord. Chem. Rev. 68 (1985) 53.
[8] L.-C. Song, M.-Y. Tang, F.-H. Su, Q.-M. Hu, Angew. Chem. Int. Ed. 45 (2006) 1130.
[9] L.-C. Song, L.-X. Wang, M.-Y. Tang, C.-G. Li, H.-B. Song, Q.-M. Hu, Organometallics 28 (2009) 3834.
[10] L.-C. Song, M.-Y. Tang, S.-Z. Mei, J.-H. Huang, Q.-M. Hu, Organometallics 26 (2007) 1575.
[11] X. Li, M. Wang, S. Zhang, J. Pan, Y. Na, J. Liu, B. Åkermark, L. Sun, J. Phys. Chem. B. 112 (2008) 8198.
[12] A.M. Kluwer, R. Kapre, F. Hartt, M. Lutz, A.L. Spek, A.M. Brouwer, P.W.N.M. van Leeuwen, J.N.H. Reek, Proc. Natl. Acad. Sci. USA 106 (2009) 10460.
[13] L.-C. Song, J.-H. Ge, X.-G. Zhang, Y. Liu, Q.-M. Hu, Eur. J. Inorg. Chem (2006) 3204.
[14] E.J. Lyon, I.P. Georgakaki, J.H. Reibenspies, M.Y. Darensbourg, Angew. Chem. Int. Ed. 38 (1999) 3178.
[15] L.A. Anderson, T.M. Loehr, R.G. Thompson, S.H. Strauss, Inorg. Chem. 29 (1990) 2142.

[16] F.T. Fat, Z. Zhou, S. Macmahon, F. Song, A. Rheingold, L. Echegoyen, D.I. Schuster, S.R. Wilson, J. Org. Chem. 69 (2004) 4602.
[17] L.-C. Song, Q.-S. Li, Z.-Y. Yang, Y.-J. Hua, H.-Z. Bian, Q.-M. Hu, Eur. J. Inorg. Chem. (2010) 1119.
[18] W. Gao, J. Liu, W. Jiang, M. Wang, L. Weng, B. Åkermark, L. Sun, C. R. Chimie 11 (2008) 915.
[19] X.-F. Liu, B.-S. Yin, J. Coord. Chem. 63 (2010) 4061.
[20] Z. Zhao, M. Wang, W. Dong, P. Li, Z. Yu, L. Sun, J. Organomet. Chem. 694 (2009) 2309.
[21] Z. Wang, W. Jiang, J. Liu, W. Jiang, Y. Wang, B. Åkermark, L. Sun, J. Organomet. Chem. 693 (2008) 2828.
[22] L.-C. Song, X.-F. Liu, J.-B. Ming, J.-H. Ge, Z.-J. Xie, Q.-M. Hu, Organometallics 29 (2010) 610.
[23] J.W. Peters, W.N. Lanzilotta, B.J. Lemon, L.C. Seefeldt, Science 282 (1998) 1853.
[24] Y. Nicolet, C. Piras, P. Legrand, C.E. Hatchikian, J.C. Fontecilla-Camps, Structure 7 (1999) 13.
[25] F. D'Souza, N.P. Rath, G.R. Deviprasad, M.E. Zandler, Chem. Commun. (2001) 267.
[26] L.-C. Song, L.-X. Wang, B.-S. Yin, Y.-L. Li, X.-G. Zhang, Y.-W. Zhang, X. Luo, Q.-M. Hu, Eur. J. Inorg. Chem. (2008) 291.
[27] F. Gloaguen, J.D. Lawrence, T.B. Rauchfuss, J. Am. Chem. Soc. 123 (2001) 9476.
[28] P. Rothemund, A. Menotti, J. Am. Chem. Soc. 70 (1948) 1808.
[29] CRYSTALCLEAR 1.3.6. Rigaku and Rigaku/MSC, The Woodlands, TX, 2005.
[30] G.M. Sheldrick, SHELXS97, A Program for Crystal Structure Solution. University of Göttingen, Germany, 1997.
[31] G.M. Sheldrick, SHELXL97, A Program for Crystal Structure Refinement. University of Göttingen, Germany, 1997.