Tuning the Photophysical and Excited State Properties of Phosphorescent Iridium(III) Complexes by Polycyclic Unit Substitution

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Two novel N-embedded polycyclic units functionalized phosphorescent iridium(III) complexes (Ir-1 and Ir-2) with substituents in different positions have been prepared. Complex Ir-1 bearing the substituent at the 3-position shows a distinct blue shift single-peak emission (524 nm) with a higher luminescence efficiency (ΦPL = 42%) and shorter emission lifetime (τ = 282 ns) by comparison with 4-position substitution based complex Ir-2 (ΦPL = 23%, τ = 562 ns), which exhibits a dual-peak emission (564 nm and 602 nm), and phosphorescence color can be tuned from green to yellow. In addition, DFT calculations demonstrate that unusual ligand-to-metal charge transfer (LMCT) excited state property can be found in Ir-2, which is in contrast to metal-to-ligand charge transfer (MLCT) excited state character in Ir-1. This result can be attributed to strong electron-donating character and 4-position substitution effect of the unit.

1. Introduction

During the past decades, transition metal complexes[a–d] are widely used in the fields of functional materials. Among them, phosphorescent iridium(III) complexes as luminescent materials have attracted more and more attentions due to their stable chemical structures, and excellent optical performances. In particular, functionalization of the cyclometalating ligand (CN ligand) can effectively control of spatial geometries, energy levels (HOMO and LUMO) and excited state characters of iridium(III) complexes, and thus further tune of photophysical properties of complexes, containing phosphorescence color, efficiency and lifetime, etc. One of simplest modification method is to introduce different substituents (electron-donating or electron-withdrawing) into CN ligand to regulate photophysical properties of complexes.[33–35] Moreover, the orbital analyses further suggest that the position of the substituent on CN ligand is also important for affecting electronic structure of the ligand. Nevertheless, most phosphorescent iridium(III) complexes usually show various common charge transfer characters in the lowest triplet excited state (T1), such as metal-to-ligand charge transfer (MLCT), intraligand charge transfer (ILCT) and ligand-to-ligand charge transfer (LLCT) excited states characters, but little for ligand-to-metal charge transfer (LMCT) character. Moreover, as a catalyst, metal complexes with LMCT excited state characters have recently been proved to be very effective in the field of photocatalytic organic synthesis.[36–37] To gain unusual LMCT character based novel phosphorescent Iridium(III) complexes, we are focus on N-embedded dioxygen-bridged polycyclic unit[38–39] with certain planarity, rigidity and strong electron-donating ability (Scheme 1), which may induce new LMCT excited states character. So it is anticipated that introduction of the unit into phosphorescent iridium(III) complex can regulate energy levels, excited state and photophysical properties.

Herein, we choose a classic green phosphorescent iridium (III) complex fac-Ir(ppy)3 (ppy = 2-phenylpyridine) as model complex, and then synthesize two novel tris-cyclometalated

Scheme 1. The structures of N-embedded polycyclic unit functionalized Iridium(III) complexes Ir-1 and Ir-2. (number 3 and number 4 represent the carbon position on the benzene ring, respectively.)
heteroleptic Iridium(III) complexes (Ir-1 and Ir-2) by introduction of N-embedded dioxygen-bridged polycyclic unit into 3- and 4- positions of phenyl ring of one ppy ligand (Scheme 1), respectively. It is found that Ir-1 shows a distinct blue shift single-peak emission with a higher luminescence efficiency and shorter emission lifetime by comparison with Ir-2, which exhibits a dual-peak emission. In addition, unusual 3LMCT excited state character can be found in Ir-2, which is in contrast to 3MLCT excited state property in Ir-1. This result can be attribute to a strong electron-donating character and 4-position substitution effect of N-embedded polycyclic unit.

2. Results and Discussion

Although their single crystal structures can not be obtained, optimized structure from DFT calculations at the B3LYP/6-31G (d) level clearly displays their spatial geometries (Figure 1b). It is found that Iridium(III) center is coordinated by two same CN ligands (ppy) and another N-embedded dioxygen-bridged polycyclic unit based CN ligand through distorted octahedral coordination geometry. In addition, N-embedded polycyclic unit of Ir-1 (torsion angels: 20.86° and 21.26°) shows very similar planarity by comparison with that of Ir-2 (torsion angels: 20.74° and 21.32°). The dihedral angle between the planar unit and the benzene ring of 2-phenylpyridine from Ir-1 (34.87°) is also the same as that of Ir-2 (34.55°) (Figure 1b). Besides, molecular polarity of Ir-1 is significantly different from that of Ir-2. Calculated dipole moment (μ) of excited state in Ir-1 (4.2346 D) is larger than that in Ir-2 (3.8716 D). In contrast, calculated μ of ground state in Ir-1 (6.8785 D) is smaller than that in Ir-2 (7.9280 D) (Figure S2 and Table S1).

As shown in Figure 2a, the spin-allowed π→π* (LC) transitions of the ligands based intense absorption bands are below 300 nm, and various charge-transfer (CT) transitions (MLCT, LLCT or ILCT) based weak low-energy absorption bands locate in the region of 310–500 nm. Notably, the lowest energy absorption bands of Ir-2 are clearly red-shifted relative to those of Ir-1, demonstrating that 4-position of N-embedded polycyclic unit substitution can efficiently lower excited-state energy level, whereas 3-position substitution has little effect on the excited state energy level.

A similar pattern of change is also reflected in their PL spectra in CH2Cl2 solution (Figure 2a). Ir-2 (λ = 564 and 602 nm) shows a significantly red shift dual-peak emission compared with Ir-1 (λ = 524 nm) with a single-peak emission. Additionally, Ir-1 displays a higher luminescence efficiency (ΦPL = 42%) and

Figure 1. Calculated optimized structures of the complex Ir-1 and Ir-2.

Figure 2. (a) Absorption and PL spectra of Ir-1 and Ir-2 and (b) their emission decay curve measured in degassed dichloromethane solution.
shorter emission lifetime ($\tau = 282$ ns) than those of Ir-2 ($\Phi_p = 23\%$, $\tau = 562$ ns) (Figure 2b and Table 1). This result suggests that 3-position of N-embedded polycyclic unit substitution can efficiently improve optical properties.

In addition, electrochemical properties of both complexes were measured by cyclic voltammetry in their CH$_2$Cl$_2$ solutions (Figure 3 and Table 1). Two oxidation potentials (Iridium(III) center and N-containing unit) are found in Ir-1 and Ir-2, which is different from only one oxidation potential for Iridium(III) center in fac-Ir(ppy)$_3$. It is noted that oxidation potentials for the Iridium(III) centers of two N-embedded polycyclic unit functionalized complexes (Ir-1: 0.46 V and Ir-2: 0.43 V) both show obvious red shift than that of fac-Ir(ppy)$_3$ (0.32 V). Besides, the oxidation potential for N-embedded polycyclic unit in Ir-1 (0.25 V) displays a remarkable blue shift in comparison with that in Ir-2 (0.31 V) (Figure 3 and Table 1). As a result, the HOMO energy level of complex can be increased more by 3-position of substitution than by 4 position, that is, the HOMO value ($-5.05$ eV) of Ir-1 is larger than that of Ir-2 ($-5.54$ eV).

To investigate the effects of N-embedded polycyclic unit and its substitution position on the excited state properties of two complexes discussed above, DFT calculations were carried out for Ir-1 and Ir-2 (Figure 4, Figure S3 and Table S2). The T$_1$ of Ir-1 originates from both HOMO-1--LUMO (52%) and HOMO--LUMO (36%) transitions, whereas Ir-2 exhibits only a HOMO--LUMO (64%) transition in T$_1$ (Figure 4 and Table S2). The HOMO of Ir-1 is mainly located in N-embedded polycyclic unit and phenyl ring of CN ligand and Iridium(III) center (contribution of d orbitals: 6.3%), the HOMO-1 mainly resides in Iridium(III) center (contribution of d orbitals: 38.3%) and phenyl ring of the CN ligands, and the LUMO is mainly distributed in 2-phenyl pyridine whereas a little on Iridium(III) center (contribution of d orbitals: 0.6%). The HOMO of Ir-2 is mainly located in N-embedded polycyclic unit and phenyl ring of CN ligand whereas a little on Iridium(III) center (contribution of d orbitals: 0.6%), and the LUMO mainly resides in 2-phenyl pyridine, phenyl ring and embedded nitrogen atom of CN ligand and Iridium(III) center (contribution of d orbitals: 1.9%). As a result, the T$_1$ transition of Ir-2 exhibits $^3$ILCT and unusual $^3$LMCT characters (Figure 4 and Table S2). This result is significant different from complexes Ir-1 with typical $^3$ILCT, $^3$LCT and $^3$MLCT characters (Figure 4). It is suggested that different positions of N-embedded polycyclic unit substitution has a great influence on the excited state properties.

### Table 1. Photophysical data of Ir(III) complexes.

| Complexes | Absorption$^{[a]}$ $\lambda$/nm $\Phi_p$ $\tau$/ns $\Phi_p$/% $\Delta$E$_{ga}$/$\Phi_p$/ev $\Delta$E$_{ga}$/ev HOMO/LUMO$^{[b]}$ $\Phi_p$/% $\tau$/ns |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Ir-1      | 232(4.75), 242(4.74), 256(4.77), 274(4.64), 288(4.70), 332(4.26), 370(4.37), 410(4.01), 450(3.49) | 524              | 0.42            | 282             | 0.25/0.46       | 0.31/0.43       | 2.50 $-5.05$/$-2.55$ |
| Ir-2      | 240(4.92), 274(4.80), 286(4.84), 330(4.31), 380(4.48), 410(4.39), 450(3.76) | 564,602          | 0.23            | 562             | 0.31/0.43       | 2.45 $-5.11$/$-2.66$ |

[a] Recorded in degassed CH$_2$Cl$_2$($3\times10^{-7}$ M) at 298 K with an excitation wavelength of 370 nm. $\Phi_p$ is referred to absolute quantum yields of phosphorescence determined by employing an integrating sphere. [b]$HOMO/E_{\text{ev}}(a) = -e\epsilon_{\text{abs},\text{onset}} + 4.8$, $E_{\text{ev}} = 1240/\lambda$, $\lambda$ is absorption wavelength threshold. LUMO$E_{\text{ev}} = E_{\text{abs}} + HOMO$

![Figure 3. Cyclic voltammograms of Ir-1, Ir-2 and fac-Ir(ppy)$_3$ in degassed CH$_2$Cl$_2$ under the scan rate of 100 mV s$^{-1}$.](image)

![Figure 4. The optimized geometries and orbital transitions of Ir-1 and Ir-2 at the lowest triplet excited state ($T_1$).](image)
3. Conclusions

We have prepared two N-embedded polycyclic unit Iridium(III) complexes functionalized in different position (3- and 4-). It is found that the strong electron-donating character of the unit and its substitution position effect both have a great influence on excited state and photophysical properties of Iridium(III) complexes. Notably, unusual LMCT excited state character can be found in 4-position substitution based complex, which is in contrast to MLCT excited state character in 3-position substitution based complex. The preliminary research results indicate that 4-position of strong electron-donating substitution is a useful strategy for the design of novel phosphorescent Iridium(III) complexes with LMCT excited state character.

Experimental Section

Synthesis and Characterization of 1-b

Intermediate 1-a was synthesized according to literature procedures.[22] 1-a (0.352 g, 1 mmol), Bis(pinacolato) diboron (0.379 g, 1.5 mmol), Pd(dppf)Cl2 (0.0229 g, 0.03 mmol) and CH2COOK (0.9814 g, 10 mmol) were charged to a 100 mL schlenck tube, followed by 15 mL 1, 4-Dioxane. The mixture was heated to 110 °C for 24 h under N2. The resulting solution was saturated with water and extracted with CH2Cl2 three times. The combined organic phase was dried and concentrated in vacuum, and target product was purified by column chromatography on silica gel with CH2Cl2/petroleum ether 1:3 (v/v) to afford green solid (1-b), 337 mg (85%).

1H NMR (400 MHz, CDCl3) δ 7.32 (d, J = 1.8 Hz, 1H), 7.30 (t, J = 3.7 Hz, 1H), 6.95 (s, 2H), 6.89 (m, 6H), 1.33 (s, 12H). 13C NMR (100 MHz, CDCl3): 147.22, 144.81, 128.89, 128.83, 128.91, 123.62, 123.44, 117.53, 117.24, 114.71, 83.89, 25.06, 24.87. C9H12N2O2 calcd: C, 72.20; N, 3.48; H, 3.16. Found: C, 72.11; N, 3.48; H, 3.16. EI-MS (m/z): 400.02 (M+), 398.00 (M++), 396.00 (M+++), 226.00 (M+++, 100%).

Synthesis and Characterization of Complex 4-Br

A mixture of 4-Br (0.073 g, 0.1 mmol), 1-b (0.048 g, 0.12 mmol), KαCO3 (2.2 g, 16 mmol) and tetra-(triphenylphosphine)-palladium (0.001 g, 0.001 mmol), followed 8 mL of water and 16 mL of dichloromethane, and the organic layer was concentrated, then target product was purified by column chromatography on silica gel with CH2Cl2/petroleum ether 1:3 (v/v) to afford yellow solid, 0.074 g, 80 %.

1H NMR (400 MHz, CDCl3) δ 8.10 (s, 1H), 7.98 (s, 2H), 7.78 (s, 2H), 7.46 (d, J = 2.1 Hz, 2H), 7.40 (d, J = 7.6 Hz, 1H), 7.59 (m, 3H), 7.53 (t, J = 5.1, 1H, 2H), 6.72 (d, 10H), 6.71 (d, J = 2.0 Hz, 1H). 13C NMR (CDCl3) δ 188.64, 164.91, 164.82, 147.12, 146.90, 146.19, 145.92, 145.36, 143.42, 137.80, 136.35, 136.20, 132.49, 130.58, 130.44, 129.75, 129.63, 122.69, 122.16, 121.13, 120.23, 120.01, 119.08, 118.41. C9H12BrN2O2 calcd: C, 54.02; N, 5.73; H, 3.16. Found: C, 53.98; N, 5.71; H, 3.21. EI-MS (m/z): 734.06 (M+, 80%).

Synthesis and Characterization of Complex Ir-1

A mixture of 4-Br (0.073 g, 0.1 mmol), 1-b (0.048 g, 0.12 mmol), KαCO3 (2.2 g, 16 mmol) and tetra-(triphenylphosphine)-palladium (0.001 g, 0.001 mmol), followed 8 mL of water and 16 mL of dichloromethane. The mixed solution was heated to 100 °C for 24 h under N2. The resulting solution was cooled to room temperature and concentrated in vacuum, extracted with water and dichloromethane, and the organic layer was concentrated, then target product was purified by column chromatography on silica gel with CH2Cl2/petroleum ether 1:3 (v/v) to afford yellow solid, 339 – 343 °C.

1H NMR (400 MHz, CDCl3) δ 8.09 (t, J = 7.9 Hz, 1H), 7.97 (d, J = 7.9 Hz, 2H), 7.87 (d, 1H), 7.72 (m, 6.2 Hz, 5H), 7.63 (m, J = 5.4 Hz, 3H), 7.38 (d, 2H), 6.97 (m, 13H), 6.85 (m, 6H). 13C NMR (CDCl3) δ 166.39, 166.06, 147.27, 147.17, 145.42, 137.18, 137.17, 136.77, 136.32, 129.71, 127.58, 124.05, 123.46, 122.39, 122.16, 121.59, 119.96, 118.03, 118.99. C13H12IrN2O2 calcd: C, 66.15; N, 6.05; H, 3.59. Found: C, 66.11; N, 6.02; H, 3.63. EI-MS (m/z): 926.25 (M+, 30%).

Synthesis and Characterization of Complex 3-Br

Ir-OTf (0.146 g, 0.225 mmol) and 2-(4-bromophenyl)pyridine (0.116 g, 0.5 mmol) were charged to a 100 mL schlenck tube, followed by ethanol (50 mL). The mixture was heated to 80 °C for 24 h under N2. The combined organic phase was dried and concentrated in vacuum, and target product was purified by column chromatography on silica gel with CH2Cl2/petroleum ether 1:2 (v/v) to afford yellow solid, 133 mg (70 %). 1H NMR (CDCl3) δ 7.87 (m, 3H), 7.62 (m, 7H), 7.49 (m, 4H), 7.03 (m, J = 2.1 Hz, 1H), 6.87 (m, J = 1.8 Hz, 9H), 6.77 (d, J = 7.3 Hz, 1H). 13C NMR (CDCl3) δ 147.14, 147.04, 146.95, 139.13, 137.15, 136.98, 136.18, 136.06, 130.10, 129.94, 125.27, 124.04, 123.89, 122.92, 122.31, 121.94, 121.86, 120.22, 120.03, 118.96, 119.80, 118.83. C6H5BrIrN2 calcd: C, 54.02; N, 5.73; H, 3.16. Found: C, 53.97; N, 5.71; H, 3.20. EI-MS/m/z: 734.12 (M+, 100%).

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Conflict of Interest

The authors declare no conflict of interest.

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[1] M. A. Baldo, M. E. Thompson, S. R. Forrest, Nature 2000, 403, 750.
[2] A. Tsuboyama, H. Iwawaki, M. Furugori, T. Mukaido, J. Kamatani, S. Igawa, T. Moriyama, T. Miura, T. Takiguchi, S. Okada, M. Hoshino, K. Ueno, J. Am. Chem. Soc. 2003, 125, 12971.
[3] C. Shi, H. Sun, X. Tang, W. Lv, H. Yan, Q. Zhao, J. Wang, W. Huang, Angew. Chem. Int. Ed. 2013, 52, 13434.
[4] C. Shi, H. Sun, Q. Jiang, Q. Zhao, J. Wang, W. Huang, H. Yan, Chem. Commun. 2013, 49, 4746.
[5] C. Jin, R. Guan, J. Wu, B. Yuan, L. Wang, J. Huang, H. Wang, L. Ji, H. Chao, Chem. Commun. 2017, 53, 10374.
[6] K. Y. Zhang, P. Gao, G. Sun, T. Zhang, X. Li, L. Liu, Q. Zhao, K. K. W. Lo, W. Huang, J. Am. Chem. Soc. 2018, 140, 7827.
[7] L. Chen, J. Song, W. Zhao, G. Yi, Z. Zhou, A. Yuan, Y. Song, Z. Wang, Z.-T. Ouyang, Dalton Trans. 2018, 47, 16596.
[8] P.-N. Lai, C. H. Bryszcz, M. K. Alam, N. A. Ayoub, T. G. Gray, J. Bao, T. S. Matar, J. Mater. Chem. A. 2018, 6, 1612.
[9] X. Guo, C. Qian, R. Shi, W. Zhang, F. Xu, S. Qian, J. Zhang, H. Yang, A. Yuan, T. Fan, Small 2019, 15, 1804855.
[10] S. Shi, D. Tu, Y. L. H. Li, Q. Zhao, W. Huang, B. Wei, S.-J. Liu, X.-H. Zhou, Q. Yu, B.-S. Xu, W. Huang, Adv. Funct. Mater. 2016, 26, 881.
[11] J. Zhang, M. Huang, B. Xi, K. Mi, A. Yuan, S. Xiong, Adv. Energy Mater. 2018, 8, 20170133.
[12] P. Tao, Y. Miao, Y. Zhang, K. Wang, H. Li, L. Li, X. Li, T. Yang, Q. Zhao, W. Huang, L. Liu, X. Zhou, B. Xu, W. Huang, Org. Electron. 2017, 45, 293.
[13] M. Huang, K. Mi, J. Zhang, H. Liu, T. Yu, A. Yuan, Q. Kong, S. Xiong, J. Mater. Chem. A. 2017, 5, 266.
[14] C. Shi, M. Huang, Q. Li, G. Xie, C. Yang, A. Yuan, Dalton Trans. 2018, 47, 17299.
[15] J. Zhang, Q. Kong, D.-Y. Wang, J. Mater. Chem. A. 2018, 6, 6376.
[16] Q. Kong, T. Wu, J. Zhang, D.-Y. Wang, Compos. Sci. Technol. 2018, 154, 136.
[17] K. Y. Zhang, Q. Yu, H. Wei, S. Liu, Q. Zhao, W. Huang, Chem. Rev. 2018, 118, 1770.
[18] M. J. Jurow, C. Mayr, T. D. Schmidt, T. Lampé, P. I. Djurovich, W. Brütting, M. E. Thompson, Nat. Mater. 2016, 15, 85.
[19] J. Lee, H.-F. Chen, T. Batagoda, C. Coburn, P. I. Djurovich, M. E. Thompson, S. R. Forrest, Nat. Mater. 2016, 15, 92.
[20] Z. Wang, Z. Zhang, J. Xia, W. Wang, S. Sun, L. Liu, H. Yang, J. Alloys Compd. 2018, 769, 969.
[21] X. Li, J. Zhang, Z. Zhao, L. Wang, H. Yang, Q. Chang, N. Jiang, Z. Liu, Z. Bian, W. Liu, Z. Lu, C. Huang, Adv. Mater. 2018, 30, 1705005.
[22] Q. Li, C. Shi, X. Zhang, Q. Zhao, A. Yuan, Eur. J. Inorg. Chem. 2019, DOI: 10.1002/ejic.201900077.
[23] D. Su, Z. Tang, J. Xie, Z. Bian, J. Zhang, D. Yang, D. Zhang, J. Wang, Y. Liu, A. Yuan, Q. Kong, Appl. Surf. Sci. 2019, 469, 487.
[24] C. Shi, Q. Li, L. Zou, Z. Li, A. Yuan, Q. Zhao, Eur. J. Inorg. Chem. 2018, 2018, 1131.
[25] J. Zhang, Q. Kong, L. Yang, D.-Y. Wang, Green Chem. 2016, 18, 3066.
[26] Q. Li, C. Shi, M. Huang, X. Wei, H. Yan, C. Yang, A. Yuan, Chem. Sci. 2019, DOI: 10.1039/C8SC04252G.
[27] Q. Li, X. Zhang, Y. Cao, C. Shi, P. Tao, Q. Zhao, A. Yuan, Dalton Trans. 2019, DOI: 10.1039/C9DT00344D.
[28] Y. Miao, P. Tao, L. Gao, X. Li, L. Wei, S. Liu, H. Wang, B. Xu, Q. Zhao, J. Mater. Chem. C. 2018, 6, 6656.
[29] P. Tao, Y. Zhang, J. Zhang, W. Wei, H. Li, L. Li, Q. Zhao, X. Zhang, S. Liu, H. Wang, W. Huang, J. Mater. Chem. C. 2017, 5, 9306.
[30] Y. Wang, X. Guo, Z. Wang, M. Liu, B. Wu, Y. Wang, C. Yan, A. Yuan, H. Yang, J. Mater. Chem. A. 2017, 5, 25562.
[31] M. Schulze, A. Steffen, F. Würthner, Angew. Chem. Int. Ed. 2015, 127, 1590.
[32] X. Guo, C. Qian, R. Shi, W. Zhang, F. Xu, S. Qian, J. Zhang, H. Yang, A. Yuan, T. Fan, Small 2019, 15, 1804855.
[33] C. Shi, D. Tu, Q. Yu, H. Liang, Y. Liu, Z. Li, H. Yan, Q. Zhao, W. Huang, Chem. Eur. J. 2014, 20, 16550.
[34] T. Kim, H. Kim, K. M. Lee, Y. S. Lee, M. H. Lee, Inorg. Chem. 2013, 52, 160.
[35] T. Liu, B.-H. Xia, X. Zhou, C.-C. Zheng, Q.-J. Pan, H.-X. Zhang, Theor. Chem. Acc. 2008, 121, 155.
[36] A. Hu, J.-J. Guo, H. Pan, Z. Zuo, Science 2018, 361, 668.
[37] A. Hu, J.-J. Guo, H. Pan, H. Tang, Z. Gao, Z. Zuo, J. Am. Chem. Soc. 2018, 140, 1612.
[38] A. Wakamiya, H. Nishihira, T. Fukushima, F. Suzuki, A. Saeki, S. Seki, I. Osaka, T. Sasamori, M. Murata, Y. Murata, H. Kaji, Angew. Chem. Int. Ed. 2014, 53, 5800.
[39] H. Nishihira, K. Tanaka, Y. Morisaki, Y. Chujo, A. Wakamiya, Y. Murata, J. Org. Chem. 2017, 82, 5242.

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