

Phosphorescent chemosensors based on heavy-metal complexes

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Recently, the use of phosphorescent heavy-metal complexes as chemosensors has attracted increasing interest due to their advantageous photophysical properties. This *critical review* focuses on the design principles and the recent development of phosphorescent chemosensors for metal cations, anions, pH, oxygen, volatile organic compounds and biomolecules based on some heavy-metal complexes (such as Pt(II)-, Ru(II)-, Re(I)-, Ir(III)-, Cu(I)-, Au(I)- and Os(II)-based complexes), in which the variation in phosphorescence signals induced by the interaction between heavy-metal complexes and analytes is utilized (217 references).

1. Introduction

Chemosensors are very important due to their implications in numerous fields, such as chemistry, biology, medicine and environmental studies.^{1–10} A chemosensor can be defined as a compound that can detect the analyte by invoking a change in one or more properties of the system, such as absorption, emission, or redox potential characteristics. Fluorescence detection, in particular, is considered to be the most effective tool for sensing applications owing to the high sensitivity, easy visualization, and short response time for detection.^{11–22}

Among all compounds used as fluorescent chemosensors, organic luminophores are most widely studied due to their rich chemical structures, easy chemical modification and highly fluorescent quantum yield.^{23–25} Recently, luminescent lanthanide complexes have been successfully applied in the field of chemosensors due to several merits, such as unique line-like emission and long luminescence lifetime in the order of

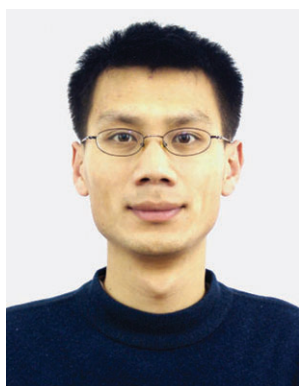
microseconds to milliseconds.^{26–30} Taking advantage of the long lifetime, the interference from short-lived background fluorescence and scattered light can be reduced to a negligible level by a method termed time-resolved fluorescence (TRF) measurement.^{31–36} Up to now, there have been some published reviews summarizing the recent developments in chemosensors based on organic luminophores or luminescent lanthanide complexes.^{2–5,10,26–31}

Heavy-metal complexes with phosphorescent emission are another kind of important luminescent metal complex.^{37–42} Different from conventional fluorescent materials, which are singlet state emitters, d⁶, d⁸ and d¹⁰ heavy-metal phosphorescent complexes are triplet emitters and have mainly been applied in organic light-emitting diodes (OLEDs). The strong metal-induced spin–orbit coupling leads to efficient singlet–triplet state mixing which eliminates the spin-forbidden nature of the radiative relaxation of the triplet state, thus enabling the enhancement of phosphorescence quantum efficiency at room temperature. Moreover, the emission wavelength, lifetime and quantum efficiency of this kind of phosphorescent material can be fine-tuned through the modification of ligand structures and metal centres.

The use of phosphorescent heavy-metal complexes (such as Pt(II)-, Ru(II)-, Re(I)-, Ir(III)-, Cu(I)-, Au(I)- and Os(II)-based

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complexes) as chemosensors has recently attracted increasing interest, as a result of the advantageous photophysical properties of heavy-metal complexes, such as sensitivity of emission properties to changes in the local environment, evident Stokes shifts for easy separation of excitation and emission, significant single-photon excitation in the visible range (even $\lambda_{\text{ex}} > 550$ nm) and relatively long lifetimes compared to those of purely organic luminophores.^{43–46} Their relatively long lifetime can endow heavy-metal complexes with a capacity for excellent temporal resolution, so their luminescence can be easily identified from fluorescent backgrounds. However, there have been few reviews concerning heavy-metal-complex-based phosphorescent chemosensors in the past decade.^{41,42,47} In light of the rapid development in this field, it is necessary to summarize the recent research results concerning phosphorescent chemosensors based on heavy-metal complexes. In this review, we confine our detailed coverage to articles published since 2001. In addition, there are also some examples of heavy-metal-complex-based chemosensors that do not exhibit any change in phosphorescent signal. Such chemosensors are not included in this review.

2. Excited state properties of phosphorescent heavy-metal complexes

Phosphorescent heavy-metal complexes mainly include Pt(II)-, Ru(II)-, Re(I)-, Ir(III)-, Cu(I)-, Au(I)- and Os(II)-based complexes with d^6 , d^8 and d^{10} electron structures. Different from the organic luminophores and luminescent lanthanide complexes, the excited state properties of heavy-metal complexes are very complicated, which is related to the rich metal centers and ligand structures. The excited states of heavy-metal complexes mainly include metal-to-ligand charge-transfer (MLCT),⁴⁸ ligand-to-ligand charge-transfer (LLCT),^{49,50} intraligand charge-transfer (ILCT),⁵¹ ligand-to-metal charge transfer (LMCT),⁵² metal-metal-to-ligand charge-transfer (MMLCT),⁵³ ligand-to-metal-metal charge transfer (LMMCT)⁵² and metal-to-ligand-ligand charge-transfer (MLLCT)^{54,55} states, which depend on the metal centers,



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chemical structures and triplet state energy levels of the ligands, local environment and intermolecular interaction. A change in excited state in one complex can lead to change in emission properties, including emission wavelength, intensity and lifetime. For example, we have recently demonstrated a new mechanism of ³MLCT-mediated phosphorescent emission for some Ir(III) complexes in which the formation of excimers by adjacent ligand π - π stacking can significantly change the excited state properties.^{54,55} To better understand and utilize the rich excited state properties of phosphorescent heavy-metal complexes is a pre-requisite for the design of phosphorescent chemosensors.

3. Design principles for phosphorescent chemosensors

3.1 Approaches for linking receptor to phosphorescent signaling unit

Generally, a chemosensor contains at least two units: a receptor unit and a signaling unit. The receptor unit can selectively bind to the analytes. The signaling unit can report the interaction between receptor and analytes through changes in optical or other properties. For phosphorescent chemosensors, the phosphorescent heavy-metal complexes act as signaling units, which translate chemical information (the analyte binding process) into an optical signal. To date, several approaches have been reported for linking the receptor to the phosphorescent signaling unit. One approach involves linking the receptor to the ligand of a complex through a spacer (Fig. 1). This is termed the “receptor- σ -signaling unit approach”. Using this “receptor- σ -signaling unit approach”, phosphorescence turn-on or turn-off chemosensors could be fabricated easily. In the second approach, the receptor is conjugated to a ligand without a spacer. This approach can be called the “receptor-conjugated signaling unit approach” (Fig. 2). On the basis of the “receptor-conjugated signaling unit approach”, not only phosphorescence intensity but also emission wavelength of the synthetic chemosensors could be modified, and to date many ratiometric phosphorescence chemosensors have been developed by this route. A further approach to realize phosphorescent chemosensors is based on an irreversible chemical reaction between a heavy-metal complex and analytes. This approach can be called the “chemodosimeter approach” (Fig. 3). Ratiometric phosphorescence probes could be easily

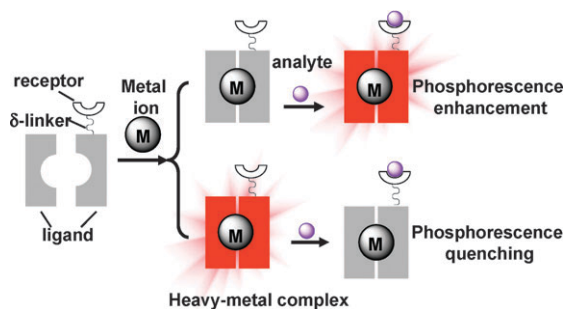


Fig. 1 “Receptor- σ -signaling unit approach” for linking receptor and signaling unit for designing phosphorescent chemosensors and possible varying phosphorescence signal responses.

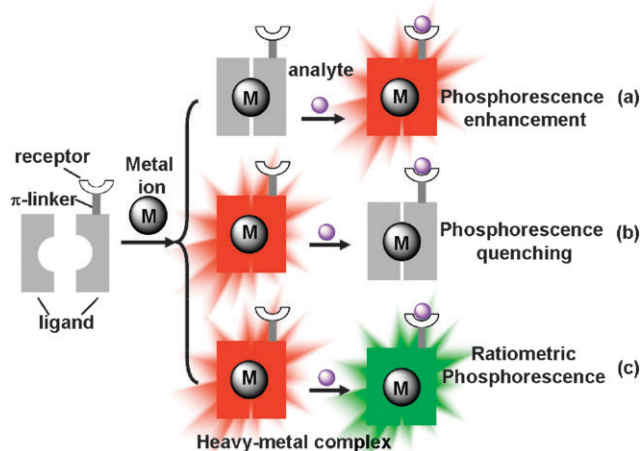


Fig. 2 “Receptor-conjugated signaling unit approach” for linking receptor and signaling unit for designing phosphorescent chemosensors and possible varying phosphorescence signal responses.

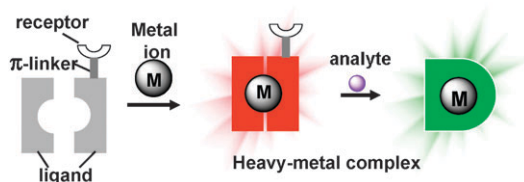


Fig. 3 “Chemodosimeter approach” for linking receptor and signaling unit for designing ratiometric phosphorescent probe.

developed by this “chemodosimeter approach”. In addition, phosphorescence turn-on chemosensors can also be realized by this route.

3.2 Sensing mechanisms of phosphorescent chemosensors

There are various mechanisms adopted for the design of a phosphorescent chemosensor.

First, the photoinduced electron transfer (PET) mechanism is adopted for the design of turn-on and turn-off phosphorescence chemosensors (mechanism I). PET often quenches the emission of complexes. The binding of receptor with analyte can inhibit (or induce) the PET and restore (or weaken) the emission. As a result, turn-on (or turn-off) phosphorescence chemosensors can be obtained. The “receptor-σ-signaling unit approach” for linking receptor and signaling unit is usually used for designing PET-based phosphorescent chemosensors.

Second, the excited state properties of phosphorescent heavy-metal complexes are very rich and different excited states can lead to different emission properties. If the receptor is connected to the ligand by a spacer or a specific recognition site is incorporated into the ligand, the interaction of the receptor with the analyte will perturb the energy levels of the excited states and induce interconversion among the different charge transfer states, thereby producing a change in phosphorescent signal and realizing the detection (mechanism II). This mechanism II of phosphorescent chemosensors is usually achieved by the “receptor-conjugated signaling unit approach” for linking receptor and signaling unit.

The third kind of mechanism is based on fluorescence resonance energy transfer (FRET) (mechanism III), which is dependent on a change in the energy transfer between energy donor and acceptor after binding with analyte.

For the d^8 and d^{10} heavy-metal complexes, there exists intermolecular metal-metal (such as $Pt \cdots Pt$ and $Au \cdots Au$) interaction,⁵⁶ which can significantly influence the excited state properties of complexes, such as the formation of 3MMLCT or 3LMMCT excited states. If the binding of complexes with analytes influences the metal-metal interaction, the emission properties can be changed. Utilizing this mechanism (mechanism IV), some novel phosphorescent chemosensors can be designed.

In addition, for some complexes, binding of the analyte can change the degree of ligand distortion, leading to a change in emission intensity. This mechanism (mechanism V) can also be adopted to design new phosphorescent chemosensors.

The phosphorescent emission of heavy-metal complexes is sensitive to the local environment. If binding of heavy-metal complexes with analyte changes local surroundings and leads to a change in phosphorescent emission, the detection can be realized (mechanism VI). This mechanism is often utilized to design phosphorescent probes for biomolecules.

The selective examples introduced in this review are mainly based on the above-mentioned sensing mechanisms.

4. Phosphorescent chemosensors for metal cations

Metal cations play very important roles in life and environmental sciences. For example, Na^+ , K^+ , Mg^{2+} and Ca^{2+} are involved in biological processes such as transmission of nerve pulses, muscle contraction and regulation of cell metabolic activity. Hg^{2+} , Pb^{2+} and Cd^{2+} are very toxic to the environment and living organisms. Hence, the qualitative detection and quantitative determination of these metal cations are of great interest in biology and environmental monitoring.^{57,58} Up to now, several kinds of phosphorescent chemosensors for metal cations based on $Pt(II)$, $Ru(II)$, $Ir(III)$, $Re(I)$ and $Au(I)$ complexes have been reported. For most phosphorescent chemosensors for metal cations, a macrocyclic moiety or nitrogen and sulfur atoms are introduced into the ligands of such complexes to provide a binding site for metal cations. In addition, the chemodosimeter approach can also be applied to the design of phosphorescent probes for metal cations.

4.1 Interaction of crown-ethers with metal cations

Complexes in which a macrocyclic binding site is pendant from a metal complex unit have been of enduring interest as sensors for metal cations.^{59–62} The binding of metal cations to the macrocyclic unit can induce a perturbation of the primary metal center, which results in a change in its photophysical properties. This kind of metal complex is often based on ligands containing macrocyclic crown-ether or aza-crown-ether components. The metal ions most commonly used as analytes are alkali-metal and alkaline-earth metal ions, which can bind well to crown-ether ligands. In the past decades, considerable work has been carried out on the development of $Ru(II)$ polypyridyl-containing crown-ether complexes as luminescent sensors. Recently, the utilization of $Pt(II)$, $Re(I)$,

Au(I) and Ir(III) complexes containing crown ethers as metal cation sensors has also been attracting increasing interest.

4.1.1 Pt(II) complexes. Pt^{2+} has a d^8 electron structure and can coordinate with $\text{N}^{\wedge}\text{N}^{\wedge}\text{N}$, $\text{N}^{\wedge}\text{N}^{\wedge}\text{C}$, $\text{N}^{\wedge}\text{N}$ or acetylide ligands. For most reported Pt(II) complex-based chemosensors for metal cations, the crown-ether receptor is often incorporated into an acetylide ligand. Complexation with metal ions can influence the photophysical properties of the Pt(II) complexes. Furthermore, the complexation can change the lowest excited state of Pt(II) complexes from a LLCT transition to a MLCT transition, inducing a change in the emission properties of Pt(II) complexes, which is in accordance with mechanism II in section 3.2. On the other hand, complexation with metal ions can block photoinduced electron transfer, in which an electron is transferred from electron-rich substituent groups (as a donor) on the alkynyl ligand to the platinum metal center to quench the emissive excited state. And this is in accordance with mechanism I in section 3.2. Hence, according to these two sensing mechanisms, the detection of metal ions can be realized by utilizing change in the emission properties of the Pt(II) complexes.

Complexes **1–3** have a similar acetylide ligand linked with the crown-ether moiety but different multidentate ligands, namely $\text{N}^{\wedge}\text{N}^{\wedge}\text{C}$ ligand for **1**, $\text{N}^{\wedge}\text{N}^{\wedge}\text{N}$ ligand for **2** and $\text{N}^{\wedge}\text{N}$ ligand for **3**. These complexes can realize turn-on phosphorescent sensing detection for metal cations. The Pt(II) complex **1** linked to the N atom of a monoaza-15-crown-5 moiety in the acetylide ligand can signal Mg^{2+} specifically by utilizing the interconversion of excited states (mechanism II in section 3.2).⁶³ In the absence of Mg^{2+} , its lowest-energy absorption arises from an $^3\text{LLCT}$ transition. Complex **1** is non-emissive due to rapid internal conversion from the $^3\text{MLCT}$ to the $^3\text{LLCT}$ state (k_{ic}) and facile non-radiative deactivation of the low-lying $^3\text{LLCT}$ state. However, the addition of Mg^{2+} induces the conversion of the lowest-energy state. Upon complexation of Mg^{2+} , the $^3\text{LLCT}$ state is shifted above the $^3\text{MLCT}$ transition in energy (see Fig. 4) and bright luminescence from the $^3\text{MLCT}$ state is observed. Importantly, the phosphorescent change can be detected by long wavelength excitation at 465 nm. For complexes **2** and **3**, the 15-crown-5 receptor is conjugated to the acetylide ligand through oxygen atoms.⁶⁴ Complex **2** is non-emissive in acetonitrile solution at room temperature. Upon addition of Ca^{2+} or Mg^{2+} ions, significant luminescence enhancements of more than 31-fold and 8-fold, respectively, are observed, suggesting the potential of this system to serve as a luminescent sensor for Mg^{2+} and Ca^{2+} ions. The luminescence switch-on of complex **2** is attributed to blocking of the intramolecular reductive electron-transfer quenching mechanism upon metal ion binding. The coordination of metal ions within the crown cavity reduces the ability of the donor atoms on the crown unit to quench the emissive $^3\text{MLCT}$ state by photoinduced electron transfer (mechanism I in section 3.2). Alternatively, the emission enhancement can also be viewed as a shift of the non-emissive $^3\text{LLCT}$ to higher energies, resulting in the $^3\text{MLCT}$ emissive state being the lowest-lying excited state (mechanism II in section 3.2), giving rise to a $^3\text{MLCT } d\pi(\text{Pt}) \rightarrow \pi^*(\text{terpyridine})$ emission. A similar luminescence switch-on effect has also

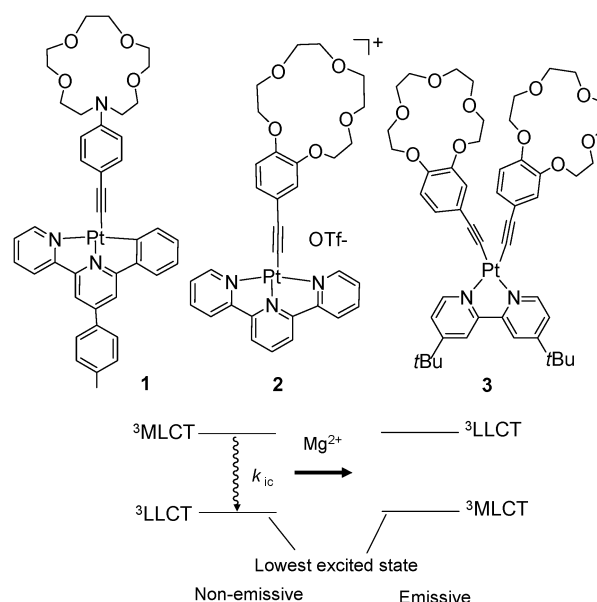
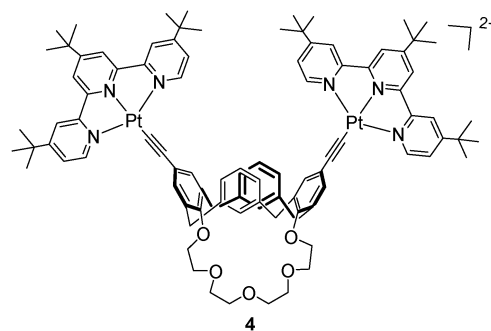


Fig. 4 Mg^{2+} induced lowest excited state conversion of complex **1** from $^3\text{LLCT}$ to $^3\text{MLCT}$.

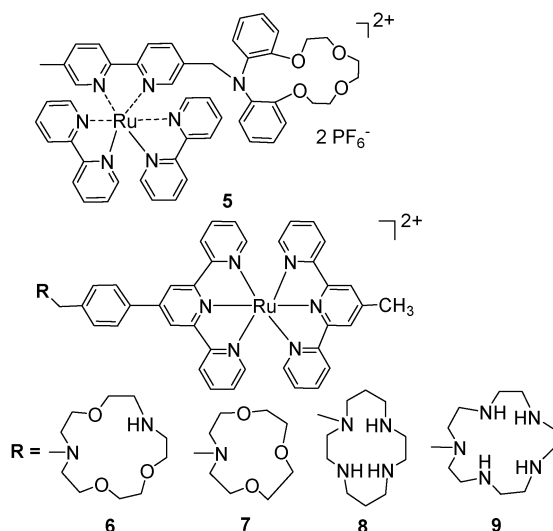
been observed for complex **3** in the presence of Zn^{2+} and Mg^{2+} .⁶⁵

Most of the reported Pt(II) complexes as chemosensors are mononuclear. Recently, Yam *et al.* have reported a novel dinuclear Pt(II) alkynylcalix[4]crown-5 complex **4**, which shows a blue shift in its emission wavelength and a concomitant substantial enhancement in its emission intensity upon metal ion-binding with excitation wavelength of 475 nm, showing more selective binding toward K^+ over other alkali metal and alkaline-earth metal ions.⁶⁶ The phosphorescent blue-shift can be rationalized in terms of lowering of the $d\pi(\text{Pt})$ orbital energy as a result of the reduced electron-donating ability of the diethynyl-calix-crown moiety upon cation inclusion, while the mechanism of the enhancement in the emission intensity may be attributed to blocking of the intramolecular reductive electron transfer as well as energy-transfer quenching pathways upon metal ion binding (mechanism I in section 3.2).

4.1.2 Ru(II) complexes. Ru^{2+} has d^6 electron structure and tends to form complexes with octahedral coordination structures. Usually, three bidentate $\text{N}^{\wedge}\text{N}$ ligands (such as bipyridine or phenanthroline ligand) or two tridentate $\text{N}^{\wedge}\text{N}^{\wedge}\text{N}$ ligand (such as terpyridine ligand) are chosen to form Ru(II) complexes. And such kind of Ru(II) complexes exhibit excellent photophysical and electrochemical properties.



For Ru(II) complexes **5–9**, the macrocyclic receptor is attached to the phosphorescent signaling unit through a spacer, which is in accordance with the “receptor– σ -signaling unit approach”. Complex **5** comprises a Ru(II) tris(2,2'-bipyridine) (Ru(bpy)₃²⁺) luminophore covalently linked to a di[(*o*-triethyleneglycoxy)phenyl]amine crown ether.⁶⁷ The addition of alkali metal cations, most notably Li⁺, restores emission by way of curtailing intramolecular electron transfer (mechanism I in section 3.2). The emission properties of **6** and **7** are pH-dependent.⁶⁸ Interestingly, complex **6** containing a diaza-15-crown-5 moiety can selectively sense Hg²⁺ in preference to Cu²⁺, Cd²⁺ and Pb²⁺. The presence of Cd²⁺ or Pb²⁺ enhances the emission intensity of **7** in the pH range of 4–6. Complexes **8** and **9** contain polyaza macrocycles. In the case of complex **8**, this macrocycle can coordinate Cu²⁺ and phosphorescence of the Ru(II) core is quenched, which is caused by an energy-transfer mechanism.⁶⁹ The change of fluorescence can be monitored by long excitation wavelength of 484 nm. The emission of complex **9** is enhanced by large heavy-metal ions and quenched by smaller ones. For example, Ni²⁺, Cu²⁺ and Cd²⁺ quench its phosphorescence intensity. In contrast, Pb²⁺ and Hg²⁺ enhance its phosphorescence.⁶⁸



Different from complexes **5–9**, the linking approach for receptor and phosphorescent signaling unit for complexes **10–13** is based on the “receptor-conjugated signaling unit approach”. These complexes contain an aza-oxa macrocycle. Complex **10** has been found to exhibit higher selectivity and specificity toward Hg²⁺ ions over alkaline-earth metal ions.⁷⁰ Interestingly, homoleptic and heteroleptic ruthenium tris(phenanthroline)s **11–13** can serve as photoluminescent systems for sensing Ba²⁺ ions, by either redox potential or luminescence measurements.⁷¹ Addition of Ba²⁺ induces significant emission enhancement and large hypsochromic shift in emission wavelength (up to 87 nm). The apparent luminescence enhancement can be attributed to the decreased electron transfer quenching by the N-aza moiety lone pair (mechanism I in section 3.2). Importantly, the hypsochromic shift in emission is assigned to the energetic lowering of the t₂ ground state, while the ³MLCT state, due to its π^* (phenanthroline) nature, is only influenced to a minor extent by the addition of Ba²⁺ ions (Fig. 5).

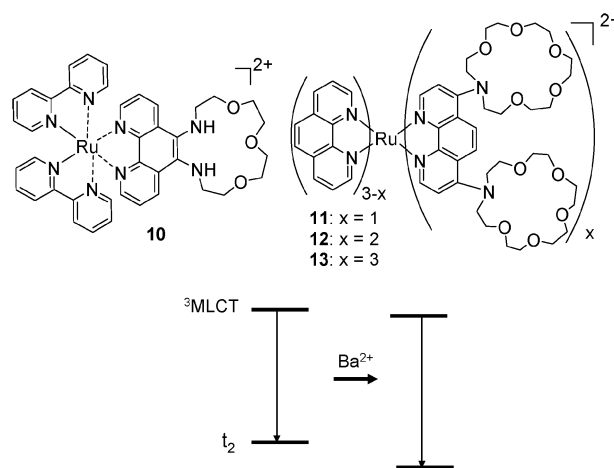
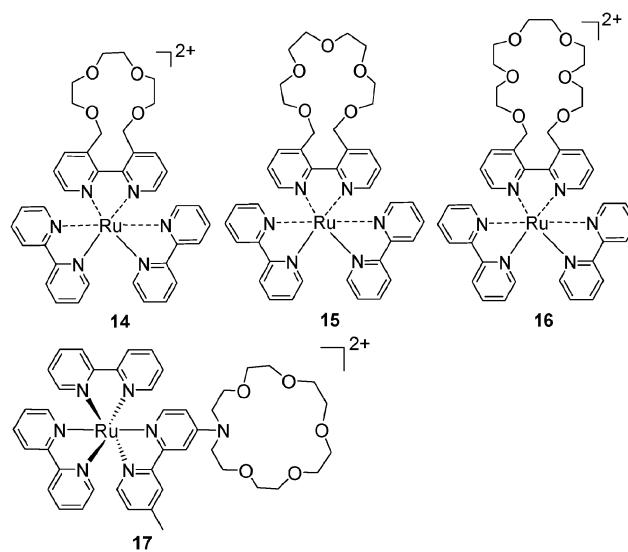


Fig. 5 Schematic representation of the energetic lowering of the ³MLCT and t₂ ground states of complexes **11–13** upon binding with Ba²⁺.

It has been shown that even small out-of-plane bipyridyl ligand distortion of the basic Ru(bpy)₃²⁺ derivatives, which results in steric or electronic effects, has important effects on photophysical properties of these complexes, such as luminescence efficiency.^{72–75} The steric repulsion between substituents at the 3,3'-positions of a bipyridyl ligand induces an angular twist about the carbon–carbon bridge head. This angle is responsible for the disruption of the π conjugation of the bipyridyl ligand and disfavors the charge transfer between the metal center and the bipyridyl ligands, leading to low emission quantum efficiency.^{76,77} Upon binding with analytes which can lead to structural changes, the phosphorescence signals can be enhanced (Fig. 6). Utilizing this kind of analyte-induced change of ligand distortion degree (mechanism V in section 3.2), novel turn-on phosphorescent sensors based on Ru(II) complexes can be designed. For example, complexes **14–16** containing a four-, five- or six-oxygen crown ether respectively, which is tethered to a bipyridine ligand at the 3,3'-position, are successful cases of complexation with metal ions inducing structural changes in the complex. For complex



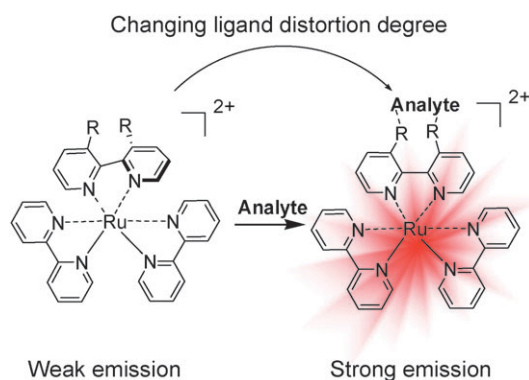


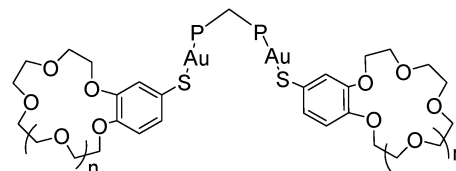
Fig. 6 Sensing mechanism of analyte-induced change in ligand distortion degree.

15,⁷⁸ the addition of Na^+ induces structural changes in the crown ether, which decreases the steric repulsion within the disubstituted bipyridine and significantly alters the emission properties of **15**. As a result, higher emission intensity in electrochemiluminescence (ECL) is observed in the presence of Na^+ . Likewise, weak allosteric interactions between Pb^{2+} ion and complexes **14** and **16** can also result in a significant increase in the emission intensity.⁷⁹ Similar to **14–16**, complex **17**, with an *N*-aza-18-crown-6 at the 4-position of one bipyridine ligand, can also be used as a phosphorescence turn-on sensor for Pb^{2+} , Hg^{2+} and Cu^{2+} ions utilizing the decreased steric repulsion upon binding of metal cations.⁸⁰ However, it is difficult to discriminate between different cations specifically.

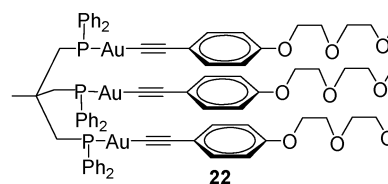
4.1.3 Au(i) complexes. Au^+ has a d^{10} electron structure and there exists intramolecular or intermolecular Au–Au interaction for many $\text{Au}(\text{i})$ complexes. Recently, some $\text{Au}(\text{i})$ complexes with $\text{Au}\cdots\text{Au}$ interaction have been demonstrated as phosphorescent chemosensors for metal cations.

The seminal work utilizing the switching on and off of the $\text{Au}\cdots\text{Au}$ interactions for chemosensors was first reported by Yam *et al.*⁸¹ They investigated the responses of a series of dinuclear $\text{Au}(\text{i})$ complexes **18–21** with different crown ether pendants to metal cations.⁵² The complexes exhibit luminescence in dichloromethane solution, which is assigned to the $\text{S} \rightarrow \text{Au}$ LMCT. Additionally these complexes show specific binding abilities toward various metal cations depending on the ring size of the crown pendants. Complexes **18** and **19** containing benzo-15-crown-5 moieties can act as luminescence ion probes for K^+ . Upon addition of K^+ , a drop in intensity at approximately 502 nm with the concomitant formation of a new long-lived, low-energy emission band at 720 nm was observed. However, for complexes **20** and **21** containing benzo-18-crown-6 pendants, the emission band at *ca.* 410 nm shows a drop in intensity with the concomitant formation of a new low-energy emission band at *ca.* 790 nm upon addition of Cs^+ ions. The low-energy band is believed to originate from a thiolate-to-gold-gold LMMCT excited state as a result of the switching-on of the $\text{Au}\cdots\text{Au}$ interaction upon Cs^+ binding to the bis(benzo-18-crown-6) moiety in a sandwich binding mode. This is a case of mechanism IV in section 3.2. The same mechanism is also applied to the polynuclear $\text{Au}(\text{i})$ phosphine/alkynyl complex **22** with three oligoether

pendants.⁸² For this polynuclear $\text{Au}(\text{i})$ complex, there exists aurophilicity resulting from weak $\text{Au}\cdots\text{Au}$ interactions. Switching-on and -off of $\text{Au}\cdots\text{Au}$ interactions can lead to the change in optical signal. The encapsulation of Mg^{2+} in between three intramolecular oligoether pendant units can turn on the $\text{Au}\cdots\text{Au}$ interactions, leading to the appearance of a new low-energy emission band at 675 nm. Hence, **22** can be utilized as a sensor for Mg^{2+} .

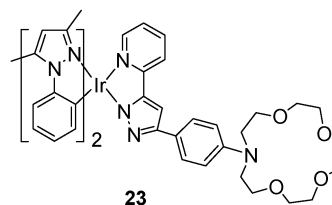


$\text{P}^{\wedge}\text{P}$ = bis(dicyclohexylphosphino)methane, $n = 1$ (**18**)
 $\text{P}^{\wedge}\text{P}$ = bis(diphenylphosphino)methane, $n = 1$ (**19**)
 $\text{P}^{\wedge}\text{P}$ = bis(dicyclohexylphosphino)methane, $n = 2$ (**20**)
 $\text{P}^{\wedge}\text{P}$ = bis(diphenylphosphino)methane, $n = 2$ (**21**)



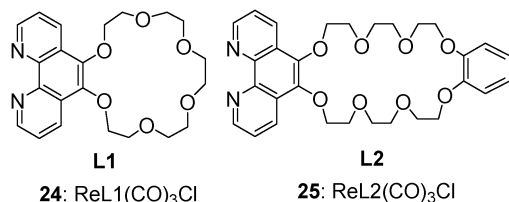
4.1.4 Ir(III) and Re(i) complexes. Other phosphorescent heavy-metal complexes containing a macrocyclic crown-ether receptor, such as $\text{Ir}(\text{III})$ and $\text{Re}(\text{i})$ complexes containing metal centers with d^6 electronic structures, can also be used as sensors for metal cations.

$\text{Ir}(\text{III})$ complex **23** with an aza-crown receptor in the pyridyl pyrazolate ligand can serve as a highly sensitive phosphorescent sensor for Ca^{2+} .⁸³ The ancillary cyclometalated phenyl pyrazole ligands, for which the $\pi\pi^*$ energy levels are far higher than those of the respective MLCT and other ligand-centered $\pi\pi^*$ excited states, enable both the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) to reside predominantly on the aza-crown-substituted pyridyl pyrazolate segment. Upon addition of Ca^{2+} , the 560 nm phosphorescence is gradually blue-shifted toward 520 nm, which is accompanied by an increase in the emission intensity. By theoretical calculation, the change in the emission spectrum during Ca^{2+} titration could be rationalized in terms of a switch of the lowest excited state transition from ILCT (*p*-dialkylaminophenyl pyrazolate \rightarrow pyridine) in **23** to LLCT (cyclometalated phenyl pyrazolate \rightarrow *p*-dialkylaminophenyl pyrazolate) in the **23**/ Ca^{2+} complex (mechanism II in section 3.2).



$\text{Re}(\text{i})$ complexes can also be used as phosphorescent sensors for cations. Complexes **24** and **25** contain a macrocyclic unit

fused to 1,10-phenanthroline by the “receptor-conjugated signaling unit approach”.⁸⁴ Both of these complexes show substantial luminescence quenching with slight red-shift in their emission maxima in acetonitrile solution upon addition of Ba^{2+} ions, with binding constants of $5.5 \times 10^5 \text{ M}^{-1}$ for **24**/ Ba^{2+} and $1.3 \times 10^5 \text{ M}^{-1}$ for **25**/ Ba^{2+} .



4.2 Interaction of sulfur or nitrogen atoms with metal cations

In addition to the use of macrocyclic receptors, there is another approach for detecting metal ions. Sulfur and nitrogen atoms can coordinate to metal cations.^{85–89} If these atoms are introduced into the ligands of complexes, the coordination between them and the metal cations can lead to changes in the photophysical properties of complexes. Hence, the detection of these cations can be realized.

4.2.1 Interaction of sulfur atoms with metal cations. It is well known that Hg^{2+} ions (*soft acid*) interact preferentially with sulfur (*soft base*).⁹⁰ If an S atom is introduced into a ligand, the specific interaction between S and Hg^{2+} can alter the emission properties of the complex, thus providing a means of detecting Hg^{2+} . An S atom can be conjugated to the cyclometalated ligand and ancillary ligand, or linked to the ligand by δ -spacer.

For Ir(III) complexes, chemical change of cyclometalated ligands affects their photoluminescent property. It can be expected that the sulfur atom, which is conjugated to cyclometalated ligands, can provide the Hg-coordinating element for Ir(III) complexes. Recently, we have demonstrated that Ir(III) complexes **26** and **27**, in which sulfur atoms are introduced to cyclometalated ligands by the “receptor-conjugated signaling unit approach”, show a highly selective recognition for Hg^{2+} with multisignaling optical-electrochemical response. Upon addition of Hg^{2+} , obvious spectral blue-shifts in the absorption and phosphorescent emission bands are measured for complex **26**.⁹¹ The solution color changes from orange to yellow-green and the emission color changes from deep-red to orange (Fig. 7), which can be observed by the naked eye. Moreover, the addition of Hg^{2+} can also cause a significant positive shift of the metal-centered Ir^{III}/Ir^{IV} oxidation wave. The evident changes in the optical and electrochemical signals can be ascribed to the interaction between Hg^{2+} and the sulfur atom of the cyclometalated ligand, which lowers the electron-donating ability of this ligand, thereby reducing the electron density on the iridium center. As a result, the HOMO energy level is lowered and the energy gap between HOMO and LUMO is increased, leading to the remarkable blue shifts in the absorption and luminescence spectra. Interestingly, unlike **26**, complex **27** displays an evident decrease in phosphorescent emission upon addition of Hg^{2+} (Fig. 8),⁹² even though they have a similar binding principle between Hg^{2+} and the sulfur atom. The different emission responses of the two complexes to Hg^{2+} can

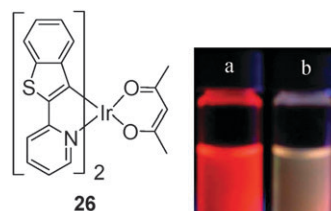


Fig. 7 Emission color observed in acetonitrile solution of **26** (500 μM) in the absence (a) and presence (b) of 1 equiv of Hg^{2+} . Adapted from ref. 91.

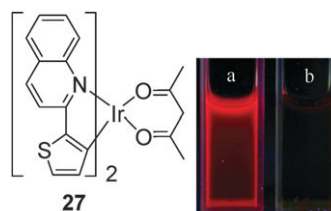
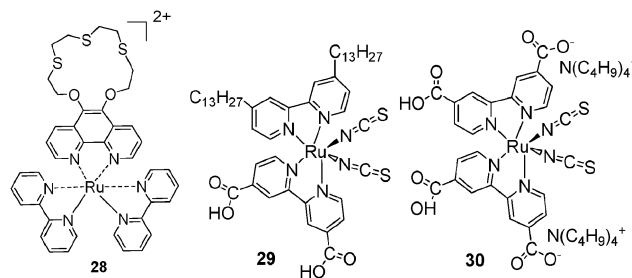


Fig. 8 Emission color observed in acetonitrile solution of **27** (500 μM) in the absence (a) and presence (b) of 1 equiv of Hg^{2+} . Adapted from ref. 92.

be ascribed to a significant difference in the charge distributions on the Hg and S atoms. The evident decrease in the emission of complex **27** after binding with Hg^{2+} can be explained in terms of electron transfer between the excited complex and the complexed Hg^{2+} cation.

The S atom can also be linked to the ligand of the heavy-metal complex by the “receptor- σ -signaling unit approach” to provide a coordinating element for Hg^{2+} . For example, the luminescence of complex **28** containing S atoms, has been found to be sensitive and selective toward the presence of Hg^{2+} ions in acetonitrile solution.⁷⁰ The emission intensity is significantly quenched by the addition of Hg^{2+} and the emission maximum undergoes a small red shift with excitation wavelength at 450 nm.



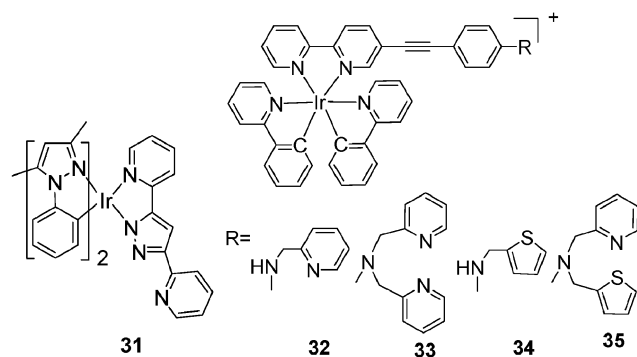
In addition, the S atom can also be linked to the ancillary ligand of the heavy-metal complex to provide a coordinating element for Hg^{2+} . Complexes **29** and **30** containing NCS groups can be used to detect Hg^{2+} in aqueous and non-aqueous solutions and when anchored to TiO_2 films by a change in color, turn-on phosphorescence, and electrochemical on and off signals.⁹³ Importantly, the phosphorescence signal change can be detected by a long excitation wavelength of 530 nm. The evident change in the photophysical and electrochemical properties is indeed a consequence of the direct

coordination of Hg^{2+} ions to the sulfur atoms of the NCS groups.

4.2.2 Interaction of nitrogen atoms with metal cations.

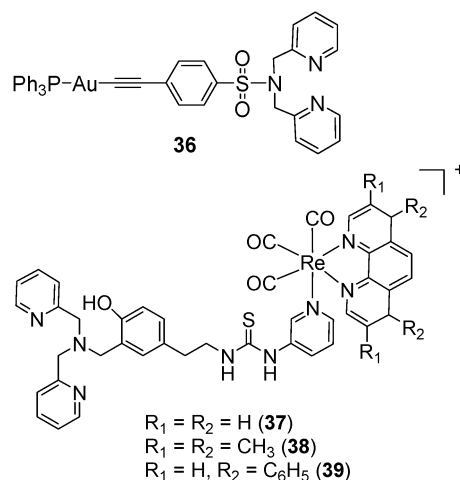
Recently, the interaction of nitrogen atoms with metal cations has also started to be utilized in designing phosphorescent chemosensors.

Chi and Chou *et al.* introduced a pyridyl group into Ir(III) complex **31**. The 3,5-di(pyridyl)pyrazole moiety can be used as a binding site for Pb^{2+} .⁹⁴ The addition of Pb^{2+} quenches the phosphorescent emission of **31**. Different from the PET mechanism of complex **31** as Pb^{2+} sensor, Ir(III) complexes **32–35** utilize the excited state conversion to detect heavy-metal ions (mechanism II in section 3.2).⁹⁵ The lowest energy excited state of these complexes containing one diimine ligand with a π -conjugated binding site is dominated by the weakly emissive intraligand charge transfer centered on the functionalized 2,2'-bipyridyl ligand. Once the binding sites are bound to a specific metal ion, such as Zn^{2+} , Cu^{2+} , Hg^{2+} and Cd^{2+} , highly luminescent $^3[\pi(2\text{-phenylpyridine}) \rightarrow \pi^*(\text{bpyC}\equiv\text{CC}_6\text{H}_4\text{-R})]$ $^3\text{LLCT}$ and $^3[\text{d}(\text{Ir}) \rightarrow \pi^*(\text{bpyC}\equiv\text{CC}_6\text{H}_4\text{-R})]$ $^3\text{MLCT}$ states are thus populated as the lowest energy excited states, resulting in a significant luminescence enhancement. In particular, complex **32** shows selective luminescence recognition of Zn^{2+} with a 25-fold luminescence enhancement. And complex **34** acts as a specific luminescence chemosensor for Cu^{2+} , exhibiting a unique off-on-off luminescence switching effect.



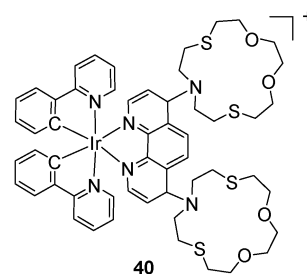
Dipicolylamine (DPA) often acts as the recognition unit for metal cations.^{96–100} The Au(I) complex **36** is found to be highly sensitive and selective toward Cu^{2+} ion.¹⁰¹ When Cu^{2+} is added to the solution of **36**, emission quenching is observed, which is due to the energy or electron transfer process caused by the d^9 electronic configuration. For Re(I) complexes **37–39** containing a tyramine-derived 2,2'-dipicolylamine (DPAT) unit, the emission from the Re(I) polypyridine unit is quenched by the DPAT moiety by the electron-transfer mechanism.¹⁰² Upon addition of Zn^{2+} and Cd^{2+} , **37–39** show emission enhancement and lifetime extension, which is attributed to the suppression of the self-quenching of the complexes through the coordination of the amine of the DPAT unit to the metal cations (mechanism I in section 3.2), leading to the observed emission enhancement and lifetime extension. Importantly, complex **39** is demonstrated to function as the first luminescent probe for intracellular

Zn^{2+} and Cd^{2+} based on a phosphorescent heavy-metal complex.



4.2.3 Interaction of both sulfur and nitrogen atoms with metal cations.

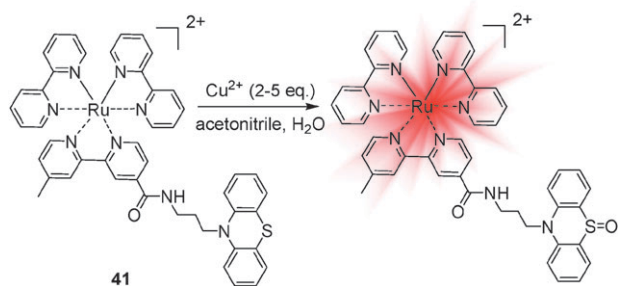
Sometimes, a heavy-metal complex as phosphorescent chemosensor is realized based on interaction of both sulfur and nitrogen atoms with a metal cation. Ir(III) complex **40** with a aza-dioxo-dithia crown ether based on the “receptor–conjugated signaling unit approach” can act as a sensitive luminescence enhancement chemosensor for Ag^+ in aqueous solution. Its emission can be mainly assigned to a ^3LC phenanthroline($\pi\text{-}\pi^*$) excited state.¹⁰³ After binding with Ag^+ , the emission is enhanced significantly (~ 3.4 fold) with a pronounced red shift in emission wavelength (~ 40 nm). The luminescence enhancement of **40** can be rationalized by a weakening of the electron donating ability of the nitrogen of the aza-dioxo-dithia crown ether moiety in **40** upon binding with Ag^+ (mechanism I in section 3.2). The red shift in emission wavelength can be explained by a lowering of the LUMO energy level, leading to the decrease in the energy gap. In addition, the excited state of **40** is changed from ^3LC to $^3\text{MLCT}$ (mechanism II in section 3.2). Utilizing this kind of Ag^+ -induced change in energy level and excited state, an excellent Ag^+ sensor is realized. In contrast, the addition of Hg^{2+} quenches the emission of **40** due to electron- or energy-transfer quenching effects of unbound Hg^{2+} ions.^{104–106}



4.3 Chemodosimeter approach

An irreversible chemical reaction between a heavy-metal complex and analytes, namely the “chemodosimeter approach”, can also be utilized to design chemosensors. However, compared with the “receptor– σ -signaling unit approach”

and “receptor–conjugated signaling unit approach”, the examples based on the “chemodosimeter approach” are very few. For complex **41**, excitation of $\text{Ru}(\text{bpy})_3^{2+}$ leads to electron transfer from the phenothiazine moiety to the MLCT excited state of $\text{Ru}(\text{bpy})_3^{2+}$, which results in the efficient quenching of luminescence.¹⁰⁷ Excess Cu^{2+} ions (2–5 equivalents) can oxidize the phenothiazine moiety to stable phenothiazine-5-oxide, which inhibits the electron transfer such that the emission of the $\text{Ru}(\text{bpy})_3^{2+}$ moiety is restored. Hence, **41** can serve as a highly selective “turn-on” luminescence chemodosimeter for Cu^{2+} .



From the above examples, we can see that many examples of phosphorescent chemosensors for metal cations have been reported. Various sensing mechanisms have been adopted to design phosphorescent chemosensors. Major linking approaches for the receptor and the phosphorescent signaling unit are based on the “receptor– σ -signaling unit approach” and “receptor–conjugated signaling unit approach”. Compared with chemosensors based on these two approaches, the examples of phosphorescent chemodosimeters for metal cations are very few. Considering the increasing success of reaction-based indicators in the past few years,¹⁰⁸ the phosphorescent chemodosimeter will be a promising approach for the realization of excellent phosphorescent chemosensors due to its superior selectivity as a result of exploiting specific reactions. However, most reported phosphorescent chemosensors for metal cations cannot be applied in aqueous solution. This is also a problem which needs to be solved in order to facilitate research in this field.

5. Phosphorescent chemosensors for anions

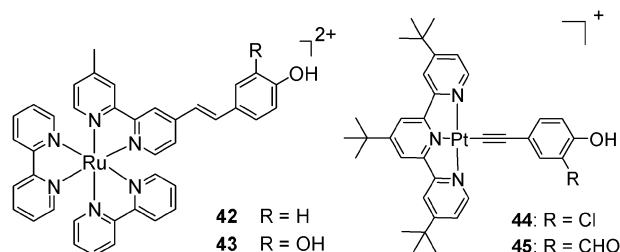
Anions, such as fluoride, chloride and phosphate, play critical roles in a range of biological processes and are implicated in a number of disease states, ranging from fluorosis to cystic fibrosis, and are thus considered important targets in terms of receptor design.^{109–112} Thus, the exploitation of new phosphorescent chemosensors for anions is very important. There are two approaches to the design of phosphorescent chemosensors for anions. One is to introduce an acidic hydrogen-containing group into the ligands of complexes. The other is to utilize the specific Lewis acid–base interaction between the boron atom and F^- to realize the detection of F^- .

5.1 Interaction of acidic hydrogen atoms with anions

Hydrogen-bonding and anion-induced deprotonation have been widely used as binding mechanisms for anion recognition.^{110,113–115} Hence, for most phosphorescent

chemosensors of anions, the design principle is to introduce groups with acidic hydrogen atoms, such as hydroxyl groups, amide, pyrrole and imidazole into the ligands of complexes. The acidity of the hydrogen atoms is crucial to the selectivity and sensitivity of sensors.

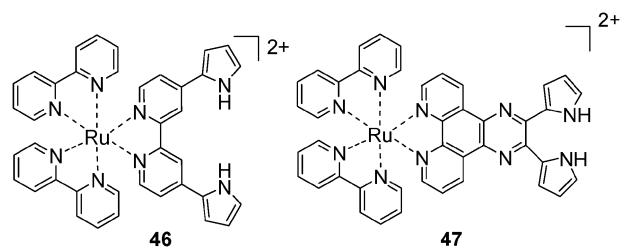
5.1.1 Hydroxyl group as receptor. The hydrogen atom of hydroxyl group is acidic. Hence, by the “receptor–conjugated signaling unit approach,” an OH-containing phenolic group can be introduced into the ligands of heavy-metal complexes to design anion sensors. For example, two $\text{Ru}(\text{II})$ complexes **42** and **43**, with pendant phenol and catechol functionalities, can act as colorimetric and phosphorescent sensors for F^- at the ppm concentration level.¹¹⁶ A detectable change in color and a decrease in emission intensity are observed upon addition of F^- . Experiments have revealed that hydrogen-bond formation occurs with a slight excess of F^- . At higher concentration of F^- , however, there is deprotonation of the OH functionality.



$\text{Pt}(\text{II})$ terpyridyl complexes **44** and **45** with phenolic ethynyl ligands can also be used as anion sensors.¹¹⁷ These complexes exhibit remarkable colorimetric responses, with color changes detectable by the naked eye, to anions such as F^- , CH_3COO^- and H_2PO_4^- . Moreover, the addition of these anions can quench the $^3\text{MLCT } d\pi(\text{Pt}) \rightarrow \pi^*(^1\text{Bu}_3\text{terpyridine})$ emission. The quenching may be ascribed to anion-induced deprotonation of the hydroxyl group. This increases the reduction potential of the phenolic ethynyl ligand and enhances the rate of electron transfer from the HOMO of the deprotonated phenolic ethynyl ligand to the $\text{Pt}(\text{II})$ terpyridyl excited state, thus inducing quenching or “switch off” of the emission.

Due to the strong acidity of phenolic group, many anions (as bases) can interact with the OH group and the selectivity of phenolic group-based anion sensors is not very high. Hence, an increasing number of NH-fragment-containing complexes are being designed as anion sensors.

5.1.2 Pyrrole as a receptor. The hydrogen atom of pyrrole is relatively acidic. It can be introduced into the ligand of a heavy-metal complex to act as an anion receptor. The $\text{Ru}(\text{II})$ fluorophore in **46** with a pyrrole-substituted bipyridine ligand provides a suitable system for the emission-based selective



detection of H_2PO_4^- at the μM level. Upon addition of H_2PO_4^- , the emission intensity of **46** at 630 nm decreases. Job plot analysis reveals a 1 : 1 host-to- H_2PO_4^- stoichiometry. The binding constant for the interaction between H_2PO_4^- and **46** is $1.0 \times 10^5 \text{ M}^{-1}$.¹¹⁸

Emission lifetime-based chemical sensing is attractive because this detection method is relatively insensitive to source variation, photobleaching of the sensor material, and changes in the efficiency of the optical system, thereby circumventing many limitations of emission-intensity-based methods. The luminescent Ru(II) complex **47**, containing a 2,3-di-(1*H*-2-pyrrolyl)quinoxaline (DPQ) receptor, was the first luminescence-lifetime-based sensor for anions.¹¹⁹ Anion-induced luminescence lifetime changes can be observed and the lifetime shortens as a function of the anion concentration. This complex clearly displays its strongest binding affinity for F^- and CN^- . Additionally the binding constants are substantially enhanced (orders of magnitude) in **47** relative to its ligand 1,10-phenanthroline-containing DPQ unit because the coordination of Ru^{2+} makes the DPQ-ligand electron-deficient and renders the pyrrolic NHs of **47** more available for hydrogen bonding to the anions.

5.1.3 Imidazole as receptor. Similar to pyrrole, the acidic hydrogen atom of the NH group in imidazole can also act as a binding site for anions. Recently, we reported that three cationic Ir(III) complexes **48–50** containing imidazolyl substituents could act as anion sensors, because the NH of the imidazolyl group can interact with anions.¹²⁰ Addition of F^- , CH_3COO^- and H_2PO_4^- causes significant changes in the UV/vis absorption and emission spectra. Solutions of **48–50** undergo a color change from yellow-green to brown, which can be observed with the naked eye (Fig. 9). Moreover, the emissions of the three complexes are quenched completely (Fig. 9). The photoinduced electron transfer process from the lone electron pair on the imidazolyl group after deprotonation quenches the emission of the complex (mechanism I in section 3.2). According to the calculated binding constant values, **48** prefers to bind F^- over the other anions. Hence, it can act as an ideal phosphorescent chemosensor for F^- .

Interestingly, the heterobimetallic Ru(II) complex **51** containing an imidazolyl fragment, selectively senses Cl^- over other anions. Cl^- can be detected through two channels: cathodic redox shift of the Fe(II)/Fe(III) redox couple and a

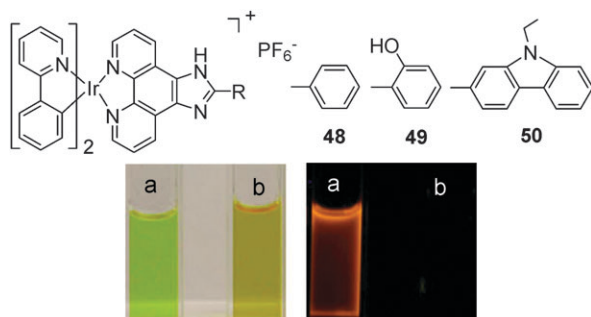
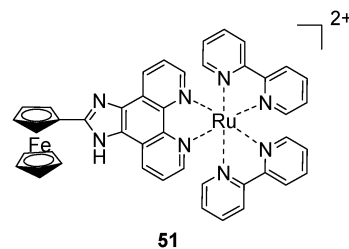
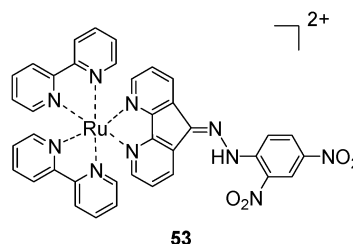


Fig. 9 Solution and emission color observed in acetonitrile solution of **48** (500 μM) in the absence (a) and presence (b) of 2 equiv. of F^- . Adapted from ref. 120.

significant red-emission enhancement. The formation of a $[\text{51} \cdot \text{Cl}^-]$ hydrogen-bonded complex is responsible for the changes in the electrochemical and emission properties.¹²¹



5.1.4 Hydrazone group as receptor. Hydrazone group can also be introduced into the ligand of the complex as anion receptor. For example, complex **52** containing a quinone-hydrazone group could be used as an F^- sensor.¹²² In the presence of F^- , proton transfer from the quinonehydrazone tautomer to this anion induces the formation of an azophenol tautomer and causes a dramatic change in color from orange to blue-violet. Furthermore, the addition of F^- also induces a significant enhancement in the luminescence intensity (Fig. 10). This Ru-based receptor shows high selectivity for F^- over other anions. The high selectivity can be attributed to the strong intramolecular $\text{N-H} \cdots \text{O}$ hydrogen bonding, and only the most electronegative anion has the potential to form additional hydrogen bonds. Similarly, complex **53** can also serve as a highly selective chromo- and fluorogenic F^- sensor.¹²³ **53** is non-emissive due to a quenching process ascribed to a PET mechanism. Upon addition of F^- , an emission peak at 625 nm appears because the presence of F^- induces deprotonation of the NH group and weakens the PET luminescence quenching process. As a result, luminescence enhancement is achieved (mechanism I in section 3.2).



5.1.5 Amide or urea as receptor. Both the amide and urea groups possess the amide $[-\text{HN}-\text{C}(=\text{O})-]$ moiety with acidic NH and can be envisaged as good binding sites for anions.¹²⁴ These two groups are the most widely used as binding sites for anions.

Complex **54** can bind two H_2PO_4^- anions by hydrogen bonding to the carboxamide NH protons, with two binding constants

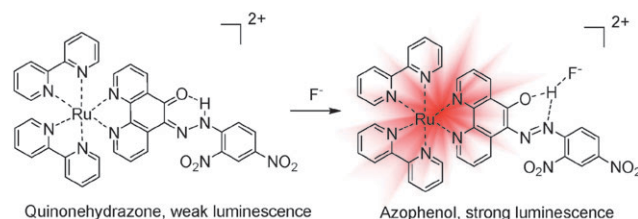
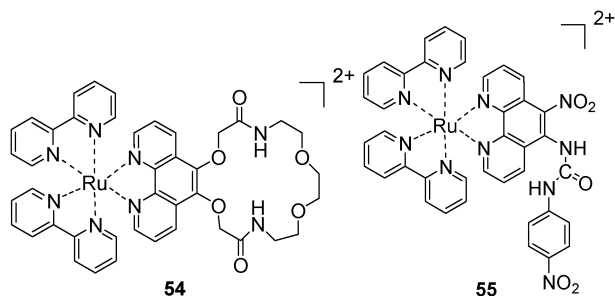


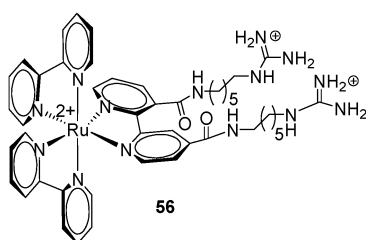
Fig. 10 F^- induced luminescence enhancement for complex **52**.

in acetonitrile ($K_1 = 1.0 \times 10^6 \text{ M}^{-1}$; $K_2 = 1.6 \times 10^6 \text{ M}^{-1}$).⁸⁴ The fact that $K_2 > K_1$ suggests a cooperative interaction, whereby binding of the first anion makes binding of the second one easier to an extent that overcomes electrostatic effects. Binding of two H_2PO_4^- anions to **54** is signalled by a five-fold luminescence intensity enhancement, possibly because of the formation of a rigid hydrogen-bonded structure that inhibits vibrational relaxation of the $^3\text{MLCT}$ state. Moreover, complex **54** undergoes complete luminescence quenching and an almost complete loss of color in the presence of F^- in acetonitrile, probably due to deprotonation of the carboxamide group.



The urea group can also act as anion receptor. The urea-based Ru(II) complex **55** can serve as an anion sensor for F^- , CH_3COO^- and H_2PO_4^- (A^-) through two different equilibrium processes, namely the formation of H-bonded adduct ($55 \cdots \text{A}^-$) and the deprotonation process ($55_{-\text{H}}^-$). Fluorescence studies have shown that the complexation of **55** with these anions can completely quench the luminescence emission, which is assigned to the faster decay of the excited triplet state owing to the narrowing of the energy gap between the excited triplet and ground singlet states. In addition, more effective solvation of the negatively charged adduct ($55 \cdots \text{A}^-$) or deprotonated form ($55_{-\text{H}}^-$) might be adding to the faster decay of the excited triplet state by nonradiative pathway.¹²⁵

5.1.6 Guanidinium as receptor. Complex **56** with guanidinium moieties as anion receptor by way of hydrogen bonding and electrostatic interactions can act as the sensor for L-glutamate and dihydrogenphosphate utilizing the mechanism of anion-induced change in ligand distortion degree (mechanism V in section 3.2).¹²⁶ The addition of L-glutamate and dihydrogenphosphate results in a significant increase in luminescence intensity with a concomitant hypsochromic shift in the maximum emission wavelength. The emission enhancement can be ascribed to a more planar conformation and rigidification of the bipyridyl receptor due to the anion complexation. In addition, the decrease in twist angle between the carbon-carbon bridge head through the simultaneous association of both guanidinium units by dicarboxylate or phosphate is contributing to the enhancement of emission.

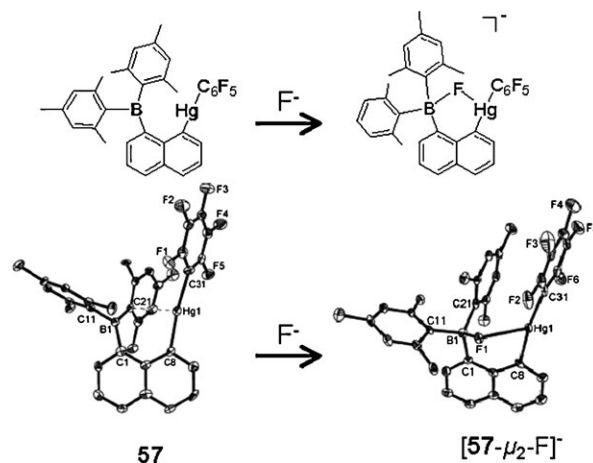


5.2 Specific Lewis acid–base interaction between the boron atom and F^-

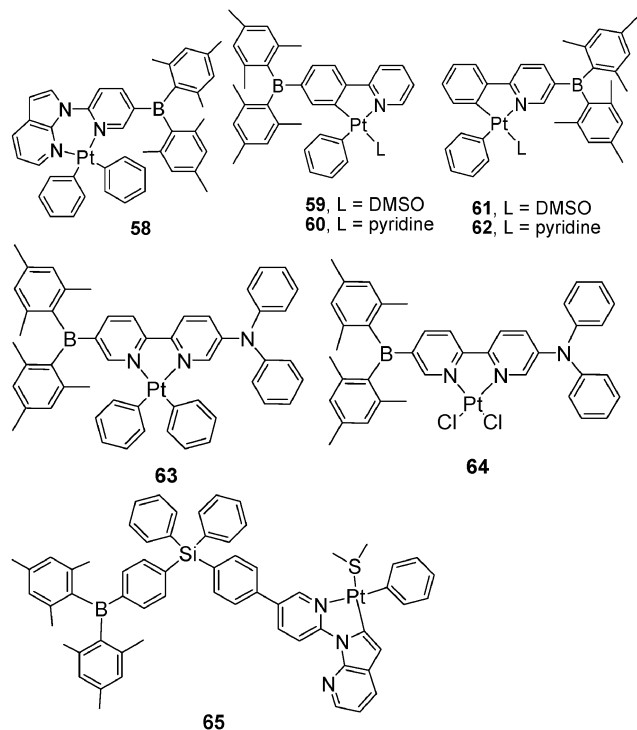
Specific Lewis acid–base interaction, such as the strong affinity of a boron atom for F^- , has been adopted as an efficient approach for fluoride detection due to the empty p_π orbital on the boron atom. Some three-coordinated boron compounds containing the dimesitylboryl (BMes_2) group have been reported to be highly selective chemosensors for F^- due to the bulky mesityl groups which render the Lewis acidic p orbital on the boron center inaccessible to all but the smallest nucleophiles.^{127–136} If BMes_2 groups are introduced into the ligands of heavy-metal complexes, phosphorescent chemosensors for F^- can be realized by utilizing the interaction of the boron atom with F^- , which can change the lowest excited state or block the intramolecular charge transfer, resulting in a change in emission properties. To date, BMes_2 group has been introduced into the ligands of Hg(II), Cu(I), Pt(II), Ir(III) and Re(I) complexes to realize phosphorescent chemosensors for F^- with excellent selectivity.

5.2.1 Hg(II) complex as signaling unit. Gabbai *et al.* reported the first example of a phosphorescent F^- sensor based on a heteronuclear B/Hg bidentate Lewis acid **57**.¹³⁷ The two Lewis acidic sites (B and Hg atoms) enforced by the 1,8-naphthalenediyl backbone promote fluoride anion chelation, which has been confirmed by crystal structures (Fig. 11). In frozen THF solution, **57** gives rise to a yellow luminescence attributed to phosphorescence of the dimesitylborylnaphthalenediyl chromophore. After binding with F^- , a white-light emission with a blue–green tint can be observed for the complex when frozen in THF at the same concentration. More importantly, **57** can also bind fluoride in partially aqueous media.

5.2.2 Pt(II) complex as signaling unit. The above phosphorescent F^- sensor **57** was only realized at low temperature. Wang *et al.* reported the first bright ambient-temperature phosphorescent Pt(II) complex **58** with a triarylboron group which displays a distinct phosphorescent response to F^- .¹³⁸ In



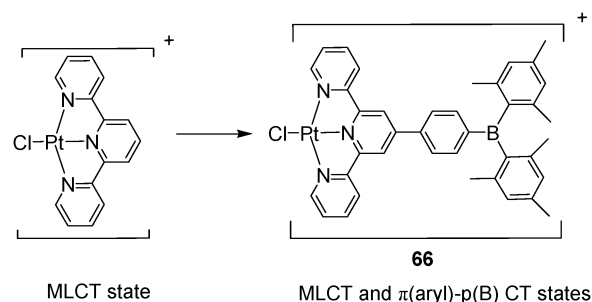
particular, the addition of F^- to a solution of **58** causes a phosphorescent color switch from yellow to green, which can be explained in terms of fluoride-induced excited state switching from MLCT to ligand-centered emission (mechanism II in section 3.2). Interestingly, complexes **59–62** with a BMe_2 group at different positions of the $C^{\wedge}N$ ligand exhibit different responsive ability to F^- .¹³⁹ Complex **59** and **60** show a weaker response to F^- than **61** and **62** do, which is attributed to weaker electron-accepting ability of the boron center for **59** and **60**. Therefore, they are most effective with the boron moiety being directly conjugated with the nitrogen heterocycle in order to enhance the electron-accepting ability and Lewis acidity. This result is very useful for the design of efficient phosphorescent F^- sensors containing a BMe_2 group.



Introducing an electron donor into the ligand containing BMe_2 group (as electron acceptor) to design heavy-metal complexes with donor–acceptor structure can create excellent phosphorescent F^- sensors. For example, $Pt(II)$ complexes **63** and **64** contain a diphenylamino group as an electron donor and BMe_2 as an electron acceptor in their bipyridine moieties.¹⁴⁰ These two complexes display a phosphorescence “turn-on” response to F^- , with a color change from orange or red–orange to whitish blue–green, which may be attributed to switching from an $N \rightarrow B$ charge-transfer transition (with possible MLCT contributions) to a $\pi \rightarrow \pi^*$ transition in the F^- adduct (mechanism II in section 3.2). Most recently, a nonconjugated donor–acceptor $Pt(II)$ complex **65**, containing a BMe_2 acceptor and an N -(2'-pyridyl)-7-azaindolyl (NPA) donor linked by a tetrahedral silane group, was also reported as F^- sensor.¹⁴¹ This compound displays ambient temperature singlet–triplet dual emission, assigned to mesityl $\rightarrow B$ charge transfer and NPA-centred $^3\pi \rightarrow \pi^*$ transition, respectively.

After binding with F^- , the triplet emission intensity is enhanced and the emission color is changed from pale green to bright yellow–green.

In addition to the above $N^{\wedge}N$ and $C^{\wedge}N$ ligands, BMe_2 acceptor was also introduced into the terpyridine ($N^{\wedge}N^{\wedge}N$) ligand of $Pt(II)$ complex to fabricate an F^- sensor.¹⁴² It is well-known that the lowest excited state of the complex $[Pt(terpyridine)Cl]^+$ is the 3MLCT state.¹⁴³ The strong room-temperature emission of complex **66** containing a BMe_2 group can be assigned to the synergetic effects of $Pt(II)$ -to-4'-phenyl(dimesitylboryl)-2,2':6',2''-terpyridine MLCT and $\pi(aryl)$ - $p(B)$ CT states. The addition of F^- leads to the emission quenching of complex **66**, which demonstrates the participation of $\pi(aryl)$ - $p(B)$ CT interactions in the excited state of **66**.



5.2.3 Ir(III) complex as signaling unit. Upon considering the excellent photophysical properties of $Ir(III)$ complexes, we introduced a BMe_2 group into the cyclometalated ligand of an $Ir(III)$ complex and thereby synthesized cationic complex **67**.¹⁴⁴ The addition of F^- induces an evident solution color change from yellow to orange–red and a pronounced on–off-type phosphorescent signaling behavior (Fig. 12), because the complexation of BMe_2 with F^- blocks the charge transfer from the Ir center to the cyclometalated ligand.

Recently, Park *et al.* also reported a neutral $Ir(III)$ complex **68** containing BMe_2 groups.¹⁴⁵ This complex exhibits both extremely high selectivity toward F^- and highly efficient two-color phosphorescence behavior at room temperature. The addition of F^- induces a red-shift in phosphorescent emission from bluish–green to orange due to a significant stabilization of frontier orbitals (preferentially the LUMO). Importantly, a clean phosphorescent signal could be obtained from the combined signal of phosphorescence and background fluorescence (from an intentionally added fluorescent impurity FITC)

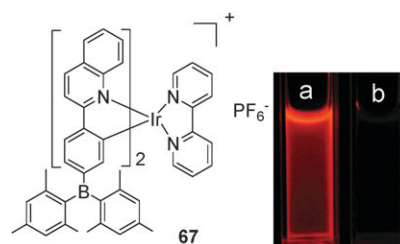


Fig. 12 Emission color observed in an acetonitrile solution of **67** (500 μM) in the absence (a) and presence (b) of 2 equiv. of F^- . Adapted from ref. 144.

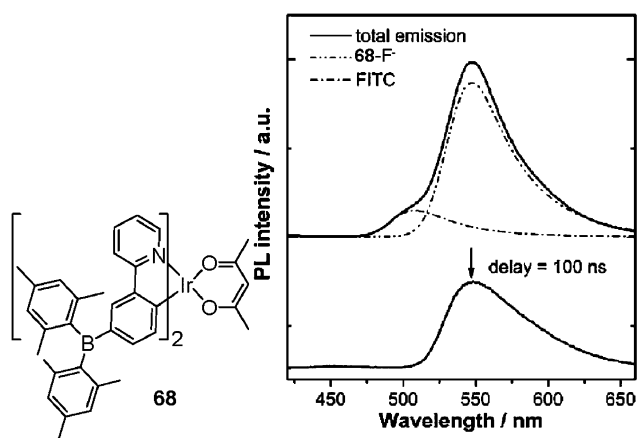
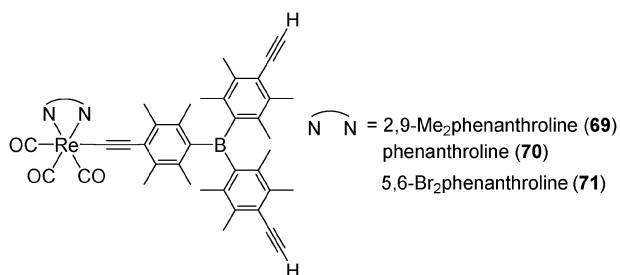


Fig. 13 Chemical structure of **68** and time-gated acquisition of phosphorescence signals: total spectrum (upper curve) and the discriminated spectrum acquired after a 100 ns delay (lower curve) of binding complex **68** and F^- (1F , $1.0 \times 10^{-5}\text{ M}$, MeCN) containing a green-fluorescent impurity (FITC). Broken lines in the upper total spectrum indicate the spectral portion of 1F and FITC. Adapted from ref. 145.

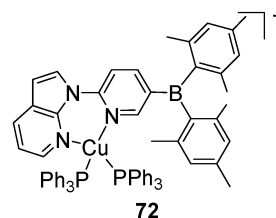
through time-gated acquisition (Fig. 13), and signal-to-noise ratio was enhanced significantly (4.4-fold). This example successfully demonstrates the advantage of long-lived phosphorescent signals over short-lived fluorescent signals in enhancing the signal-to-noise ratio.

5.2.4 Re(I) complex as signaling unit. The photophysical properties of Re(I) tricarbonyl diimine complexes are dominated by the MLCT excited state. Most recently, Re(I) complexes **69–71**, containing an alkynyl ligand linked by a triarylboron moiety, were used as F^- sensors.¹⁴⁶ These three complexes display a moderately intense emission band in THF solution at 550–750 nm, which is assigned to the excited states of $^3\text{MLCT}$ [$\text{d}\pi(\text{Re}) \rightarrow \pi^*(\text{diimine})$] origin, with some mixing of $^3\text{LLCT}$ [$\pi(\text{C}\equiv\text{CR}) \rightarrow \pi^*(\text{diimine})$] character. The addition of F^- induces a decrease in emission intensity, which can be assigned to the blocking of the intramolecular charge transfer and the interruption of the π conjugation extended through the boron atom due to the occupation of the empty p orbital of the boron atom by F^- .



5.2.5 Cu(I) complex as signaling unit. Wang *et al.* reported bright ambient-temperature phosphorescent Cu(I) complex **72** with a triarylboron group, which displays a special phosphorescent response to F^- .¹³⁸ The addition of <0.8 equiv of fluoride ions under nitrogen results in quenching of its

phosphorescent peak and a rise in the N^N ligand fluorescent peak, which is subsequently quenched with additional fluoride ions due to the F^- induced ligand dissociation. The consequence of the instability of **72** toward fluoride ions is that it has the potential to serve as a turn-on sensor for fluoride ions at $[\text{F}^-]/[\text{72}] < 0.8$ under air because the phosphorescent emission of **72** is mostly suppressed by oxygen and the fluorescence of N^N ligand is switched on in this concentration regime.



Utilizing the strong affinity of the boron atom for F^- , excellent phosphorescent chemosensors for F^- with high selectivity have been realized. However, most of these examples cannot detect F^- in aqueous media due to the high hydration energy of the small F^- . To realize the detection of F^- in aqueous environments, two points should be considered. One is the solubility of the phosphorescent chemosensor in aqueous media. The other is the very strong interaction between the phosphorescent chemosensor and F^- . Hence, this will be a new research goal in this field.

6. Phosphorescent pH sensors

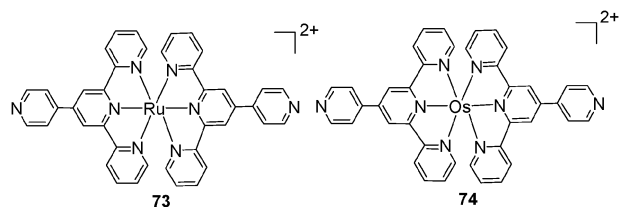
The general approach to design of pH-sensitive phosphorescent metal complexes is to append a protonatable/deprotonatable group to a ligand. Typically, an alcohol, acid or amine function is attached to the ligand of a heavy-metal complex (such as 2,2-bipyridine or 1,10-phenanthroline of Ru complex, and terpyridine of Pt complex) to provide the pH-sensitive element. The reversible acid–base interconversion can cause significant optical variations of the complexes.

6.1 Phosphorescent sensors sensitive to acid

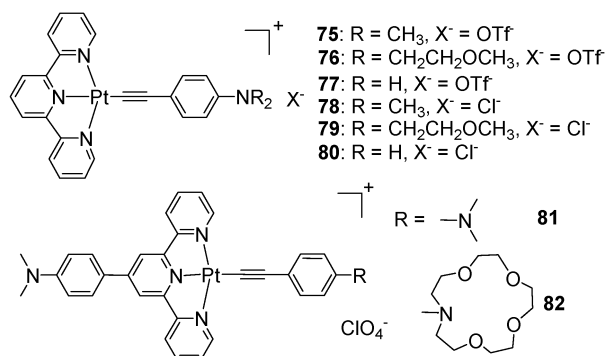
Introducing a proton acceptor into the ligand can realize phosphorescent sensors sensitive to acid. Typically, nitrogen atoms are the standard proton acceptors.

Pyridine containing nitrogen atom is basic and is usually used as a proton acceptor. For example, two homologous terpyridine-type Ru(II) and Os(II) complexes **73** and **74**, bearing a pyridine unit in the 5'-position of each terpyridine ligand, are sensitive to acid.¹⁴⁷ The addition of protons can affect their absorption and luminescence spectra. For both complexes, the absorption and luminescence bands shift to lower energies upon increasing the concentration of protons. Additionally the luminescence of the Ru complex is switched on by adding protons, whereas that of the Os complex is switched off. Three differently protonated forms are formed during this process, namely deprotonated form, monoprotonated form and bis-protonated form. At basic pH values (above *ca.* 6.5) only the deprotonated form is present in solution, whereas at acidic pH values (below *ca.* 1.5)

only the bis-protonated complex exists. At pH values between 1.5 and 6.5 the three different forms coexist.



As an important basic unit, the amino group is usually introduced into a heavy-metal complex to sense the pH value. Pt(II) terpyridyl alkynyl complexes **75–80** contain basic amino functionalities on alkynyl ligands,¹⁴⁸ and can function as colorimetric and luminescent pH sensors. Upon introduction of an acid, they show dramatic and reversible color changes and luminescence enhancement. The drastic blue-shift of the low-energy LLCT absorption band is ascribed to protonation of the amino group, which decreases the electron-donating ability of the alkynyl ligand. The dramatic emission enhancement is probably a result of the shift of the ³LLCT state to higher energies as well as of the blocking of a reductive electron-transfer quenching pathway upon protonation of the amino group, giving rise to a ³MLCT [$d\pi(\text{Pt}) \rightarrow \pi^*(\text{terpyridine})$] emission (mechanism I and II in section 3.2).



Unlike for **75–80**, the amino group is introduced into both terpyridine and acetylide ligands for complexes **81** and **82**. Their excited-state properties are also affected by pH value (see Fig. 14).¹⁴⁹ In neutral or basic solution, **81** and **82** show a lowest-lying LLCT transition from the amino-substituted acetylide to the aminophenyl-substituted terpyridyl acceptor. Upon addition of an acid to the solution, the amino group on the acetylide ligand is protonated, and the lowest-lying excited state of **81** and **82** is switched from the LLCT to the ILCT state, based on the transition from the π orbital of the phenyl unit to the π^* orbital of the metal-bound terpyridyl moiety. In

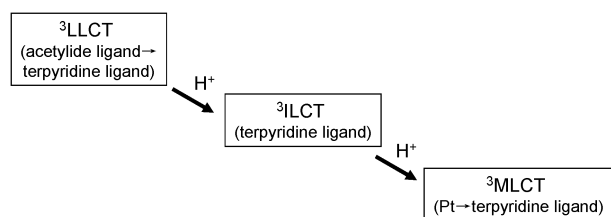


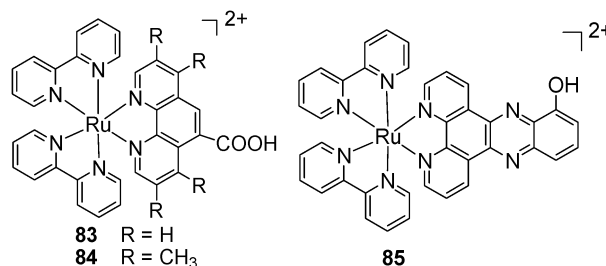
Fig. 14 Changes in excited states of **81** and **82** induced by acid.

the presence of a sufficient amount of acid, the amino group of the terpyridyl ligand is also protonated, and the lowest-lying excited state is further promoted to the $d\pi(\text{Pt}) \rightarrow \pi^*(\text{terpyridine})$ MLCT state. This switching of different excited states is fully reversible. Subsequent addition of a base to the protonated **81** or **82** leads first to switching of the MLCT state to the ILCT state, and then to the LLCT state.

6.2 Phosphorescent sensors sensitive to base

Introducing acidic hydrogen atoms (such as carboxylic acid, phenolic group) into the ligands of complexes can realize phosphorescent pH sensors sensitive to base.

Typically, as the pH-sensitive unit, carboxylic acid containing acidic hydrogen atom is introduced into phosphorescent complexes. For example, complexes **83** and **84** contain pH-sensitive 5-carboxy-1,10-phenanthroline moieties, which show monotonic changes in both emission intensity and lifetime with pH over the range $2.0 < \text{pH} < 9.0$.¹⁵⁰ The deprotonated form of the complexes is the stronger emitter and longer-lived species. Importantly, the dependence of lifetime on pH can enable lifetime-based detection for pH.



Similarly, the UV/vis absorption and emission spectra of complex **85** are pH-dependent. This system has been shown to act as a “turn-on”-type pH emission chemosensor with a large on-off ratio of ~ 150 driven by deprotonation of the hydroxy group over the pH range 6.0–11.5, which is assigned to the much increased nonradiative decay routes.¹⁵¹

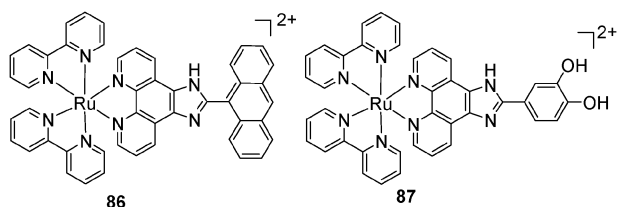
6.3 Phosphorescent sensors sensitive to both acid and base

Imidazole containing a proton acceptor (N atom) and a proton donor (N–H group) is sensitive to both acid and base.

For example, Ru(II) complex **86**, containing an imidazole unit, can serve as a sensitive spectroscopic pH sensor.¹⁵² Upon increasing the pH from 0.05 to 4.00, the emission bands are blue-shifted from 633 to 609 nm with increasing intensities. Upon further raising the pH from 6.00 to 10.5, the emission intensities decrease as the maxima red-shift from 613 nm to 617 nm. The obvious changes in emission spectra are assigned to two distinct excited-state deprotonation processes, namely dissociation of the proton on the protonated imidazole ring and deprotonation of the neutral imidazole ring.

Ru(II) complex **87**, containing both phenolic and imidazole units as deprotonatable/protonatable groups, has also been demonstrated to be a sensitive pH sensor with a luminescence modulation factor (the ratio of maximum luminescence intensity to the minimum value) of ~ 20 .¹⁵³ Four different excited-state deprotonation processes are observed, which are ascribed to deprotonation of the imino group (protonated

cation) of the imidazole ring, the 3-hydroxyl group, the neutral imidazole ring, and the 4-hydroxyl group, respectively.



7. Phosphorescent gas sensors

Realizing the detection of some gas molecules, such as oxygen, or vapours of volatile organic compounds, is very important in many fields, such as life and environmental sciences. To date, many phosphorescent gas sensors for oxygen or vapours of volatile organic compounds have been reported.

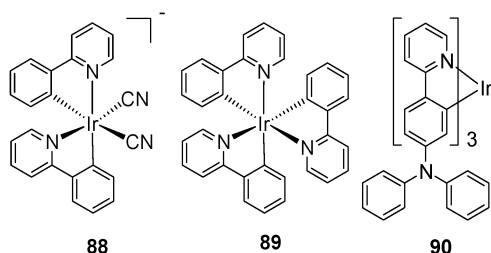
7.1 Phosphorescent sensors for oxygen

Oxygen, being essential for life, is a very important chemical species. Its detection, based on optical sensors is required in numerous areas, including oceanography, meteorology, biology, environmental science, and life science.^{154–157} For optical oxygen sensors, a particularly attractive method is based on the luminescence quenching of a phosphorescent emitter by the presence of oxygen. Oxygen is a powerful quencher of the long-lived triplet excited state of the phosphorescent emitter through efficient energy transfer with the triplet ground state of molecular oxygen. Currently, some Ru(II) polypyridyl complexes, Pt(II) and Pd(II) porphyrins, and cyclometalated complexes of Pt(II) and Ir(III) have been used as optical oxygen sensors.

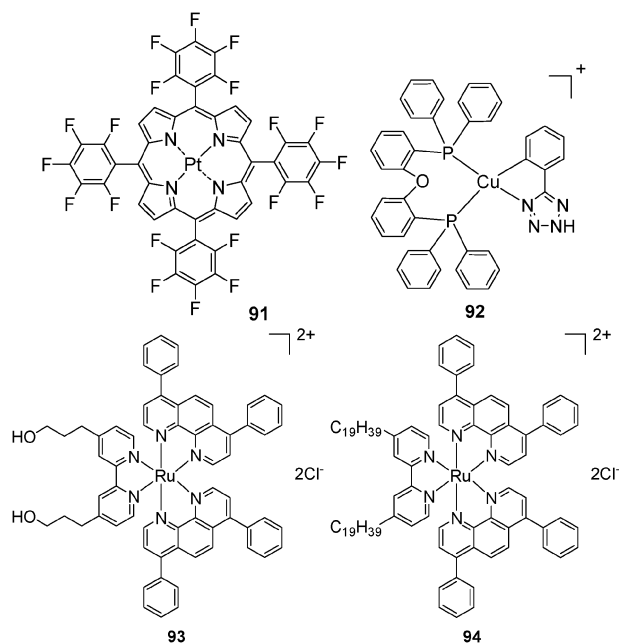
7.1.1 Phosphorescent oxygen sensors based on films.

Typically, oxygen-sensing phosphorescent materials are developed in such a way that the heavy-metal complex is dissolved or otherwise immobilized in a solid matrix such as polymers,^{158–160} sol-gel derived silica-based materials^{161,162} and Langmuir–Blodgett (LB) monolayer films.¹⁶³

Polymers are good hosts due to their easy processability. For example, Manners and Winnik *et al.* fabricated polythionylphosphazene films doped with Ir(III) complexes **88** and **89** as oxygen sensing devices.¹⁵⁸ Recently, Chan and Yersin *et al.* found that Ir(III) complex **90** displays high sensitivity to change in oxygen partial pressure even for air pressures as high as 1500 mbar when dissolved in ethyl cellulose.¹⁶⁴ The excellent oxygen sensing capabilities of this complex can be ascribed to its long emission lifetime, high phosphorescence quantum yield, and good solubility in organic solvents and in organic polymers.



Silica-based materials derived by the sol-gel process are also good hosts for phosphorescent complexes as oxygen sensors. By using Pt(II) complex **91** embedded in an organically modified silica matrix as an oxygen-sensing layer, Chen *et al.* developed an optical oxygen sensor strip with a background color layer based on CdTe quantum dots as an internal fluorescence standard.¹⁶⁵ The sensor can be applied both in rapid colorimetric oxygen detection with high resolution up to 0.50% and in quantitative analysis. The change of color originates from the change in fluorescence intensity of the oxygen-sensing layer, leading to the change in the emission intensity ratio of oxygen-sensing layer to background color layer. Another silica-based oxygen sensor is based on mesostructured matrix MCM-41 doped with a phosphorescent Cu(I) complex. Complex **92** shows bright bluish-green emission in the solid state and its emission intensity is highly sensitive to O₂ concentration.¹⁶⁶ By doping mesostructured matrix with **92**, the resulting composite material exhibits high sensitivity even at low oxygen concentrations. Moreover, when the concentration of oxygen is only 10%, the quenching of luminescence can be over 70%.



By immobilizing an Ru(II) complex on glass surfaces by covalent attachment (for complex **93**) or LB deposition (for complex **94**), two kinds of sensitive single-layered oxygen-sensing films were realized.¹⁶³ Both the prepared films achieve very high quenching efficiencies of *ca.* 95 and 88%, respectively. The higher quenching efficiency was obtained for the film fabricated by covalent attachment (film 1) rather than the film fabricated by LB deposition (film 2) or other films based on matrix supports. The high quenching efficiency of film 1 can be rationalized by the single-layered structure of the Ru(II) complex as well as the projection of the Ru(II) polypyridyl moieties away from the glass substrate, resulting in good and even exposure of probe complexes to the sensing medium.

7.1.2 Phosphorescent oxygen sensors based on crystals. The above examples are all based on composite materials of phosphorescent complexes and solid matrix. In addition to these composite materials, some complex crystals with void space channels can also be applied to detect oxygen. Mann *et al.* found that several crystals of emissive $\text{Ru}(\text{bpy})_3^{2+}$, $\text{Ru}(\text{phen})_3^{2+}$ and $\text{Ru}(5,6\text{-Me}_2\text{phen})_3^{2+}$ salts with significant void space can act as gas-phase and aqueous-solution oxygen molecule sensors.^{167,168} The void space channels (Fig. 15) are important for oxygen quenching in these systems because they allow oxygen molecules to freely move in the crystals.

7.2 Phosphorescent sensors for vapours of volatile organic compounds (VOCs)

Phosphorescent heavy-metal complexes containing d^6 , d^8 or d^{10} metal ions can also be used as vapochromic and vapoluminescent materials to detect volatile organic compounds *via* changes in color and luminescence with short response time. The VOCs-induced response usually originates from a change in the metal–metal distances, hydrogen bonding or π – π interactions in the excited state of the complexes.

7.2.1 Pt(II) complexes. To date, the most widely studied heavy-metal complex-based vapochromic and vapoluminescent materials are square-planar Pt(II) complexes. The photophysical properties of planar Pt(II) complexes containing $\text{N}^{\wedge}\text{N}$, $\text{C}^{\wedge}\text{N}^{\wedge}\text{C}$ or $\text{N}^{\wedge}\text{N}^{\wedge}\text{N}$ ligand strongly depend on the $\text{Pt}\cdots\text{Pt}$ interaction and $\pi\cdots\pi$ interaction of ligands. Upon exposure to the vapours of VOCs, these interactions of Pt(II) complexes can be influenced, leading to a change in photophysical properties and thereby the detection to VOCs.

On the basis of the $\text{Pt}\cdots\text{Pt}$ interaction, Pt(II) complexes **95–103** have been demonstrated as phosphorescent sensors for VOCs. For example, upon exposure to methanol vapor, the terpyridine Pt(II) complex **95** changes color from red to orange,

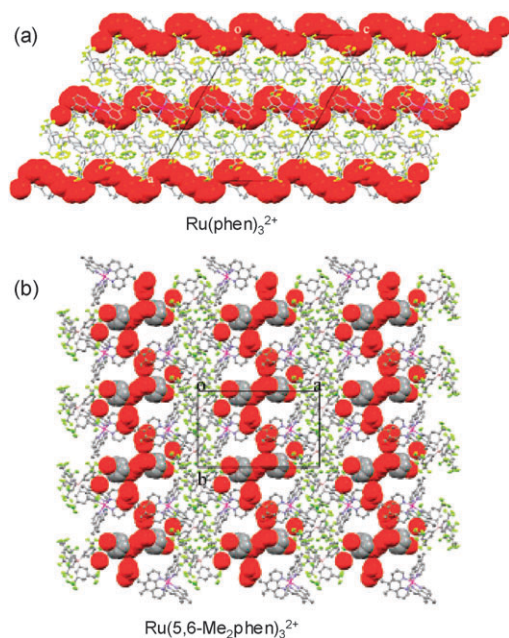
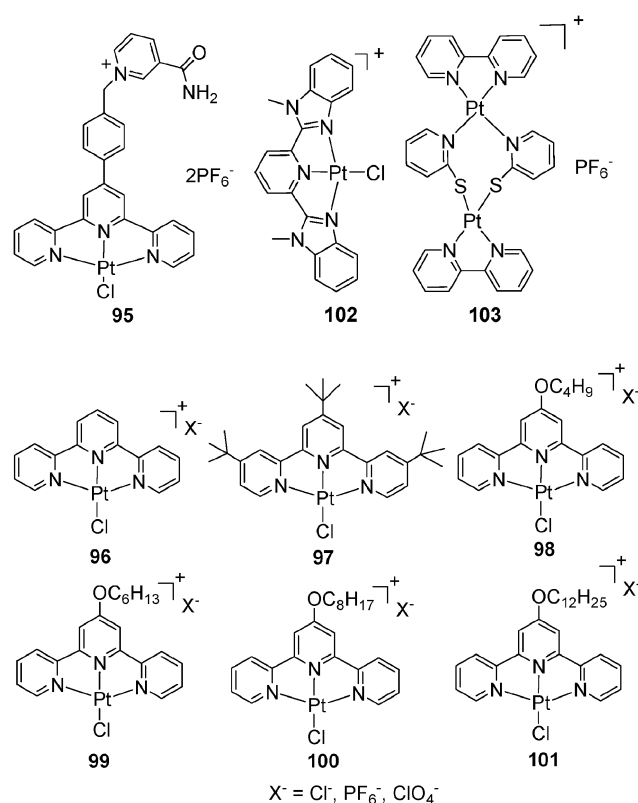


Fig. 15 Crystal stacking structures of $\text{Ru}(\text{phen})_3^{2+}$ (a) and $\text{Ru}(5,6\text{-Me}_2\text{phen})_3^{2+}$ (b) salts. Adapted from refs. 167 and 168.

and the emission maximum is blue-shifted with an increase in emission intensity.¹⁶⁹ Crystal structure analysis reveals that the spatial and geometric differences between the two forms explain the distinct color changes. The red form possesses significant $\text{Pt}\cdots\text{Pt}$ interaction and the excited state properties can be assigned to the $^3\text{MMLCT}$ state. However, for the orange form, $\text{Pt}\cdots\text{Pt}$ interaction is much weaker than for the red form and $^3\text{MLCT}$ state dominates the excited state. The changes in $\text{Pt}\cdots\text{Pt}$ interaction and excited states induced by methanol vapor are responsible for the vapochromism (mechanism IV in section 3.2). Recently, Castellano *et al.* demonstrated the possibility to assemble vapochromic and vapoluminescent microarrays for pattern recognition using the distinct cross-reactive Pt(II) terpyridyl chloride complexes (**96–101**) possessing relevant variation in ligand structure and counterion, which can respond distinctively to different analytes.¹⁷⁰



Interestingly, different anions can induce different vapochromisms for Pt(II) complexes. As shown in Fig. 16, complex **102** with the Cl^- salt only responds to vapors of methanol, chloroform, ethanol and acetonitrile, exhibiting a

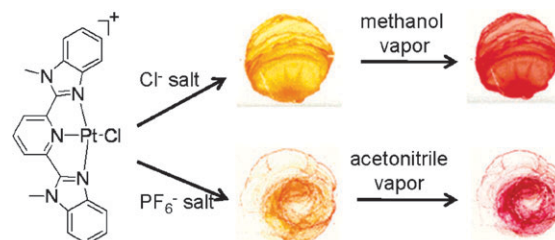
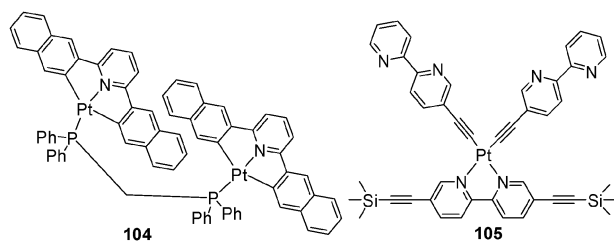


Fig. 16 Different vapochromism of Pt(II) complex **102** with different anions. Adapted from ref. 171.

distinct change in color from yellow to red. However, its PF_6^- salt only responds to acetonitrile vapor, changing from yellow to violet. This is the first example of simple Pt(II) salts based on the Cl^- and PF_6^- salts of complex **102** that exhibit vapochromic behavior.¹⁷¹ The vapochromic behavior is probably caused by the decrease in $\text{Pt} \cdots \text{Pt}$ separation accompanying vapor sorption. In addition, Kato *et al.* found that the *syn* isomer of a dinuclear Pt(II) complex **103** exhibits remarkable vapor-induced luminescence change in the presence of organic vapors such as acetonitrile or ethanol, whereas the *anti* isomer of **103** does not exhibit vapochromism.¹⁷² The single-crystal analysis indicates that a channel in the *syn* isomer allows the organic vapor to easily penetrate the crystal and change the $\text{Pt} \cdots \text{Pt}$ interactions. For the *anti* isomer of **103**, no such channel is found within the crystal structure.

Besides the $\text{Pt} \cdots \text{Pt}$ interaction, other interactions (such as $\pi \cdots \pi$ interaction) are also introduced to fabricate Pt(II) complexes as VOC sensors. The dinuclear Pt(II) complex **104** containing extended π -conjugated cyclometalated ligands shows a fast and reversible vapoluminescent response to volatile halogenated solvents (except CCl_4).¹⁷³ Accessible solvent channels and the presence of weak and reversible non-covalent $\text{C-H} \cdots \pi$, $\pi \cdots \pi$, $\text{C-H} \cdots \text{Cl}$ and $\text{Cl} \cdots \text{Cl}$ interactions are responsible for the vapoluminescent behavior of **104**. Comparative powder X-ray diffraction studies reveal that the desolvation of crystal **104** leads to a more condensed packing of the molecules, which may be the reason for the quenching of the excimeric $^3\pi\pi^*$ emission from the cyclometalated $\text{C}^{\wedge}\text{N}^{\wedge}\text{C}$ ligand. Upon exposure of the VOC molecules, the unit cell volume of **104** expands and the separation between molecules increases, leading to a decrease in the quenching and a restoration of emission intensity to that found in the solvated solid **104**. In addition, Pt(II) complex **105** exhibits selective and reversible color changes in response to a variety of organic vapours with an emission wavelength shift from 562 to 747 nm, which depends on the $\text{Pt} \cdots \text{Pt}$ distances, π - π and $\text{C-H} \cdots \pi(\text{C}\equiv\text{C})$ interactions in the stacking of the square-planar platinum(II) moieties.¹⁷⁴



In addition to the Pt(II) complexes containing multidentate of the type $[\text{PtL}_4][\text{M}(\text{CN})_4]$ ($\text{M} = \text{Pt}, \text{Pd}$; $\text{L} = \text{aryl isonitrile}$) showed emissive behaviors which are modified by exposure to vapors of VOCs.^{175,176} They also investigated the application of neutral compound $\text{Pt}(\text{CN-}p\text{-(C}_2\text{H}_5)_2\text{C}_6\text{H}_4)_2(\text{CN})_2$ as vapochromic and vapoluminescent materials.¹⁷⁷ A crystalline orange polymorph of $\text{Pt}(\text{CN-}p\text{-(C}_2\text{H}_5)_2\text{C}_6\text{H}_4)_2(\text{CN})_2$ through recrystallization was obtained and its structure arranges with linear chains of Pt atoms and solvent channels parallel with the *c* axis. Interestingly, the crystalline orange polymorph of $\text{Pt}(\text{CN-}p\text{-(C}_2\text{H}_5)_2\text{C}_6\text{H}_4)_2(\text{CN})_2$ is vapochromic and vapoluminescent. Its

unit cell changes that occur upon exposure to toluene vapor are accompanied by large, reversible blue shifts in the emission spectrum. Similar shifts also occur for benzene, chlorobenzene, mesitylene, *p*-xylene and ethanol.

7.2.2 Au(I) complexes. Utilizing the switching on and off of $\text{Au} \cdots \text{Au}$ interaction, Au(I) complexes can be used as vapochromic and vapoluminescent materials. Balch *et al.* have demonstrated the solvoluminescence behaviour of a series of Au(I) complexes utilizing the intermolecular $\text{Au} \cdots \text{Au}$ interaction.^{178–180} Eisenberg *et al.* reported the vapochromism and VOC-induced luminescence behaviour of complex $[\text{Au}(\text{S}_2\text{CN}(\text{C}_5\text{H}_{11})_2)_2]$.¹⁸¹ Intermolecular Au-Au distances of 2.9617(7) Å in the emissive solvated orange form and 8.135 Å in the non-emissive colourless form were observed in their crystal structures. Interestingly, when the colourless form was brought in contact with polar aprotic solvent vapors, such as acetone, CH_3CN , CH_2Cl_2 and CHCl_3 , luminescence could be restored. The formation of linear $\text{Au} \cdots \text{Au}$ chains induced by solvent triggered its orange colour and luminescence nature.

Similar to pure Au(I) complexes, Au/heterometal complexes can also be applied as vapochromic and vapoluminescent materials. For example, Leznoff *et al.* reported that four polymorphic forms (α , β , γ and δ) of the complex $\text{Zn}[\text{Au}(\text{CN})_2]_2$ reversibly act as very sensitive sensors of ammonia vapor, changing their structures and emission energies as ammonia is bound (Fig. 17).¹⁸² In this case, the d^{10} Zn(II) cation adopts several geometries encompassing coordination numbers from two to six. This flexibility facilitates the structural rearrangement which occurs as the ammonia interacts with the Zn(II) center, leading to a change in the gold–gold distance and thus the emission energy.

Another Au/heterometal complex acting as a vapochromic and vapoluminescent sensor is complex $\{\text{Ti}[\text{Au}(\text{C}_6\text{Cl}_5)_2]\}_n$ consisting of 1-D linear polymer chains (Fig. 18).¹⁸³ Its crystal structure has channels that run parallel to the *z* axis with

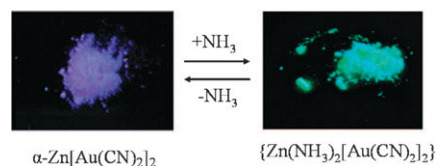


Fig. 17 (left) Powder of $\alpha\text{-Zn}[\text{Au}(\text{CN})_2]_2$ under UV. Exposure to ammonia yields the compound $\{\text{Zn}(\text{NH}_3)_2[\text{Au}(\text{CN})_2]_2\}$ (right) with bright green luminescence. Adapted from ref. 182.

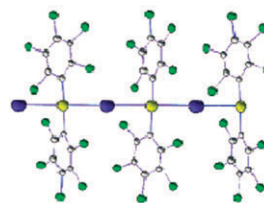


Fig. 18 Polymeric molecular structure of $\{\text{Ti}[\text{Au}(\text{C}_6\text{Cl}_5)_2]\}_n$. The Au and Ti atoms are labeled by yellow and blue, respectively. Adapted from ref. 183.

interatom distances in the range of 3.231–4.076 Å. There are holes with diameters as large as 10.471 Å (the static Au–Au distance between chains) which can accommodate the molecules entering the lattice. This complex exhibits vapochromic and vapoluminescent behavior with reversible changes of color and shifts of emission bands upon exposure to a variety of organic vapors; these behaviors are associated with a weak interaction of the Tl(I) centers with the VOCs. In addition, complex $\{\text{Ag}_2(\text{EtOEt})_2[\text{Au}(\text{C}_6\text{F}_5)_2]_2\}_n$ shows obvious vapochromic behavior toward VOCs (acetonitrile, acetone and tetrahydrofuran).¹⁸⁴ The reaction of VOCs vapors with the complex in the solid state produces complete substitution of the ether molecules by the VOC, leading to changes in color and emission wavelength.

7.2.3 Cu(I) complexes. Cu(I) halide adducts CuXL (X = halide, L = nitrogen donor ligand), as another class of d^{10} metal complexes, are particularly fascinating because they not only show a great variety of structural formats but also are often brightly luminescent even at ambient temperature, and the emission behavior varies markedly with structure and environment. Utilizing these properties, Cu(I) halide adducts can be applied as phosphorescent sensors for VOCs. Cariati and Ford *et al.* reported the luminescence vapochromism for the two $[\text{CuI}(\text{4-pic})]_n$ (**I**, $n = 4$; **II**, $n = \infty$; 4-pic = 4-picoline) solids associated with the reversible interconversion of the two Cu(I) isomers.^{185,186} Upon exposure of the solid polymeric material $[\text{CuI}(\text{4-pic})]_4$ (**II**) to toluene vapors, the blue-emitting compound **II** was transformed into yellow-emitting **I** with cubane phase. The reverse process, the transformation from **I** to **II**, can be achieved by exposing $[\text{CuI}(\text{4-pic})]_4$ solid to pentane vapors. Moreover, the transformations were carried out many times on individual samples.

7.2.4 Ir(III) complexes. The applications of Ir(III) complexes as vapochromic and vapoluminescent materials are very few. Recently, we demonstrated the first example of cyclometalated heteroleptic Ir(III) complex **106** exhibiting unique and fast vapochromic and vapoluminescent behavior (Fig. 19).¹⁸⁷ This complex can exist in both black and red form in the solid state. The black form is found to exhibit weak luminescence. In the solid-state packing of the black **106**·0.25EtOH·0.5CHCl₃ crystal (Fig. 19), the shortest distance between the oxygen of ethanol and the hydrogen atoms of **106** is found to be 3.27 Å, and thus the potential interaction between the solvent and the complex is very weak. Upon exposure to acetonitrile or propionitrile vapor, the black form immediately transforms into the red form with an intense luminescence enhancement (Fig. 19). From the solid-state packing of the red **106**·CH₃CN crystal (Fig. 19), each acetonitrile molecule is found to be involved in several interactions with its neighbors, containing $\text{N}\cdots\text{H}-\text{C}$ -type and possible $\pi(\text{C}\equiv\text{N})\cdots\text{H}-\text{C}$ -type weak hydrogen bonds, which lead to a large total interaction energy due to the cooperative effect among these weak hydrogen bonds. Hence, once the acetonitrile vapor arrives at the black form, the ethanol is replaced and the packing manner is changed. In addition, on the basis of theoretical calculation, the strong electronic coupling between the HOMOs and weak electronic coupling

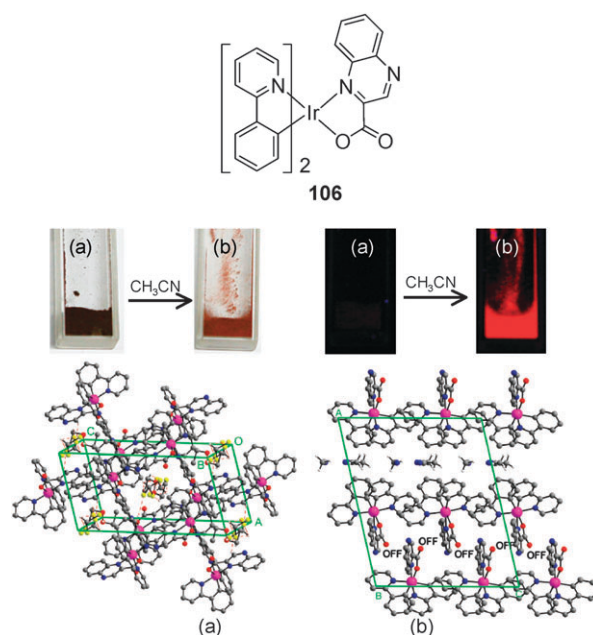


Fig. 19 Color, emission color and solid-state packing of **106** in the absence (a) and presence (b) of acetonitrile vapor. Adapted from ref. 187.

between the LUMOs of the $\pi-\pi$ dimer for the red form are responsible for the stronger emission intensity of the red form than that of black form.

8. Phosphorescent chemodosimeters for amino acids

There are several examples of the detection of cysteine (Cys), homocysteine (Hcy) and histidine based on phosphorescent heavy-metal complexes.

8.1 Phosphorescent chemodosimeters for homocysteine and cysteine

As the only two thiol-containing amino acids in the human body, cysteine (Cys) and homocysteine (Hcy) are crucial to the physiological balance in living systems.^{188–191} Deficiency of Cys may lead to several diseases, such as hematopoiesis decrease, leucocyte loss, and psoriasis, while Hcy is a risk factor for cardiovascular¹⁹² and Alzheimer's disease.¹⁹³ Recently, utilizing the selective reaction of the aldehyde group with cysteine/homocysteine to form thiazinane, Pt(II) complex **107** bearing an aldehyde group was used as a phosphorescent chemodosimeter for Cys and Hcy.¹⁹⁴ Upon addition of Hcy or Cys to its acetonitrile–water solution, an evident luminescent color change from green to orange was observed (Fig. 20). ¹H NMR studies confirm the selective reaction of the aldehyde group of **107** with Hcy to form thiazinane. Interestingly, Ir(III) complex **108** bearing an aldehyde group was demonstrated as a highly selective phosphorescence chemodosimeter for Hcy based on a similar mechanism (Fig. 21).¹⁹⁵ The addition of Hcy causes an obvious spectral blue-shift and emission enhancement, which can be observed with the naked eye. However, the addition of an excess of Cys only leads to weak enhancement of luminescent intensity. Surface charge analysis

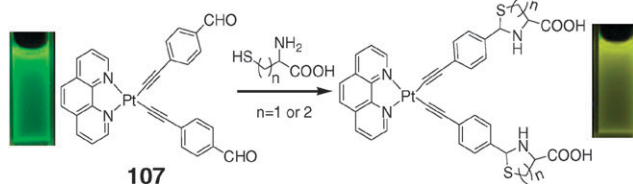


Fig. 20 Emission color observed in acetonitrile–water solution (pH 7.2, 4 : 1 v/v) of **107** (40 μ M) in the absence (a) and presence (b) of 100 equiv. of cysteine ($n = 1$) or homocysteine ($n = 2$). Adapted from ref. 194.

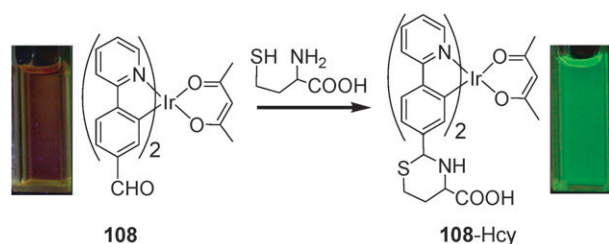
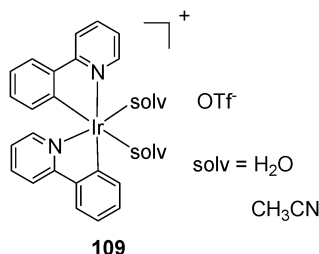


Fig. 21 Emission color observed in DMSO–HEPES buffer solution (50 mM, pH 7.2, 9 : 1 v/v) of **108** (20 μ M) in the absence and presence of 200 equiv. of homocysteine. Adapted from ref. 195.

and the electrochemical measurement indicate that a photo-induced electron-transfer process in **108**-Cys might be responsible for the high specificity of **108** toward Hcy over Cys.

8.2 Phosphorescent chemodosimeters for histidine and its derivatives

Histidine and histidine-rich proteins play a pivotal role in biochemistry and molecular biology. An abnormal level of histidine-rich proteins is an indicator for many diseases, such as thrombotic disorders, asthma, advanced liver cirrhosis, AIDS, renal disease, pulmonary disorders and malaria.^{196–201} Wong *et al.* reported a highly selective luminescent switch-on probe (complex **109**) with high sensitivity toward histidine/histidine-rich proteins.²⁰² The complex is weakly emissive in phosphate-buffered saline (PBS). In the presence of histidine, it exhibits a 180-fold increase in emission intensity. The establishment of a covalent bond between complex **109** and the imidazole moiety of histidine is responsible for the emission switch-on.



9. Phosphorescent probes for other biomolecules

In addition to the detection of amino acids, there are also some examples of phosphorescent probes for detecting other biomolecules, such as thymidine 5'-triphosphate (TTP), nucleic acids, proteins and glucose.

9.1 Phosphorescent probes for TTP

TTP is an essential building block for DNA replication and cell division.²⁰³ The phosphorescent sensor **110** for TTP based on an Ir(III) complex was realized through a donor (mCP–Zn²⁺–cyclen; mCP = *N,N'*-dicarbazolyl-3,5-benzene)–acceptor (FIrpic–bis(Zn²⁺–dipicolylamine conjugate)) ensemble system.²⁰⁴ Selective recognition of TTP from other nucleotides followed by luminescence enhancement of TTP is achieved by the strong binding of the thymine unit to Zn²⁺–cyclen and intermolecular energy transfer between the mCP and FIrpic moieties (mechanism III). This example provides a new paradigm for the design of sensors: through the introduction of receptor into both energy donor and acceptor, the binding of receptor with analyte can induce energy transfer from donor to acceptor, leading to the enhanced emission and realization of detection of analyte (Fig. 22). This paradigm will be helpful in the design of novel sensors.

9.2 Phosphorescent probes for nucleic acids

Nucleic acids are the most fundamental and important class of biomolecules in a living cell. Their detection and characterization are therefore of great importance, which would not only help us to understand how the cell functions and to assist biological research, but also facilitate the development of new tools for disease diagnosis and treatment and developments of new drug.

Yam *et al.* demonstrated a general label-free method for optical sensing and characterization of single-stranded nucleic acid.²⁰⁵ The electrostatic binding of positively charged Pt(II) complex **111** to single-stranded nucleic acids carrying multiple negative charges can induce the aggregation and self-assembly of planar Pt(II) complexes, leading to remarkable changes in

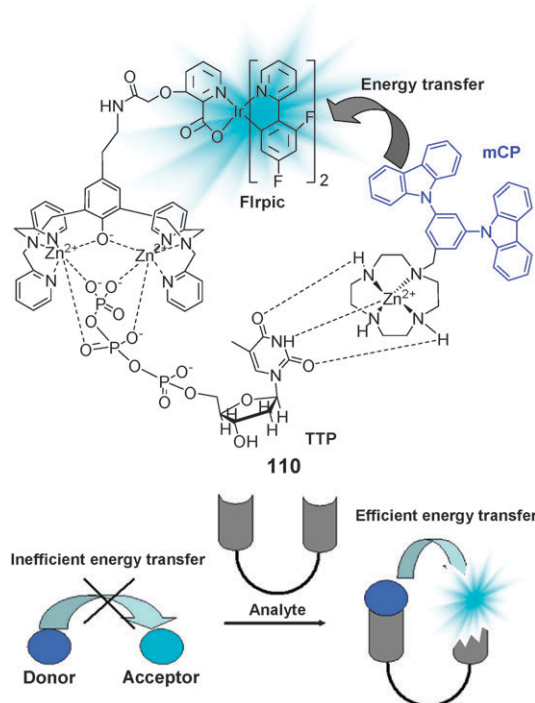
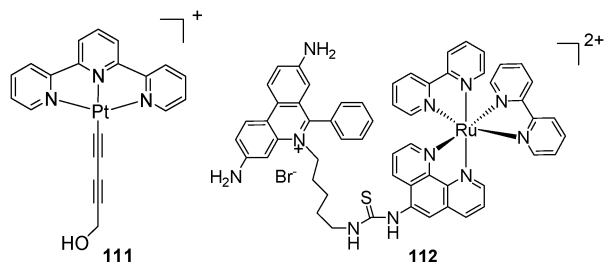


Fig. 22 Paradigm of analyte induced energy transfer.

optical properties ascribed to the transition of MMLCT (mechanism IV in section 3.2). Furthermore, they realized the detection of DNA G-quadruplex formation and nuclease activity through aggregation-induced spectral changes of Pt(II) complex **111**.²⁰⁶



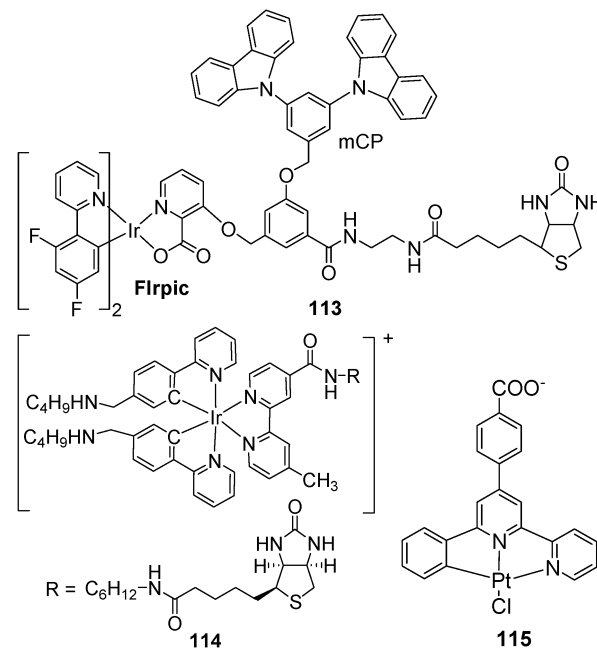
Phenanthridine derivatives, such as ethidium bromide and propidium iodide, are a kind of widely used probe for detecting the presence of duplex nucleic acids.²⁰⁷ Turro *et al.* introduced a phenanthridine moiety to Ru(II) complex **112** and found that this complex can act as a RNA probe with a nine-fold enhancement in signal intensity and a fluorescence lifetime many times greater than that of other phenanthridine derivatives in the presence of RNA, making it especially useful for time-resolved detection in complex biological solutions such as cell growth medium.²⁰⁸ Using the time-resolved method, the signal-to-noise ratio was increased from 3 to over 13.

9.3 Phosphorescent probes for proteins

Biotin binds to the glycoprotein avidin with a very high affinity, and the biotin–avidin interaction has been widely utilized in immunology, *in situ* hybridization, and affinity chromatography.²⁰⁹ Such kind of special interaction can also be utilized in the design of phosphorescent biological probes based on ionic Ir(III), Re(I) and Ru(II) complexes,^{210,211} making use of the sensitivity of emission properties of heavy-metal complexes to the local environment (mechanism VI in section 3.2). The increased hydrophobicity and rigidity of the local surroundings of the bound probes, compared with the environment of the free probes, lead to the luminescence enhancement of complexes.^{212,213} Lo *et al.* have developed several kinds of phosphorescent biological probes based on ionic Ir(III), Re(I) and Ru(II) complexes and some of their research works have been summarized in their recent review articles.^{210,211} Recently, Hong *et al.* have reported a neutral tripod system **113** for FRET-based biotin–avidin assays containing an energy acceptor Flrpic, an energy donor mCP and biotin.²¹⁴ A dramatic increase in luminescence intensity is observed upon binding to avidin. This neutral sensing system for biotin–avidin assays offers remarkable sensitivity over traditional ionic complex-based probes, due to the intramolecular energy transfer and increased hydrophobicity associated with the avidin binding site and neutral probe **113**.

Different from most examples utilizing the emission enhancement properties of phosphorescent probes, Lo *et al.* found that complexes **114** containing biotin exhibited dual-emissive properties.²¹⁵ For this complex, one structured high-energy band at about 492 nm is observed in buffer under aerated condition. The binding of **114** to avidin leads to a decrease in its high-energy emission intensity and the

development of a low-energy emission feature at about 608 nm with a sharp isoemissive point at 574 nm, ascribed to the increased hydrophobicity of the local environment of the complex upon protein binding.



Che *et al.* found that Pt(II) complex **115** can be used as a highly sensitive luminescence switch-on protein-binding probe.²¹⁶ Protein binding induces an evident increase in emission intensity, which is due to a change in the structural distortion of **115** in its triplet excited state. Furthermore, this complex can be used for the staining of protein mixtures in 1D and 2D SDS-PAGE (SDS = sodium dodecyl sulfate; PAGE = polyacrylamide gel electrophoresis) without interfering with peptide-mass fingerprinting analysis, and can be used in live cell imaging.

9.4 Phosphorescent probes for glucose

The accurate estimation of blood glucose concentration is vitally important for preterm infants during critical care and is used extensively in the management of diabetes mellitus. Designing a phosphorescent probe for glucose is of great utility.

Osmium complexes exhibit electrochemical reversibility and stability in both their oxidized and reduced states, leading to a difference in the emission spectra of the reduced and oxidized forms. Accordingly, for complex **116**, the oxidized complex has a maximum emission intensity at $\lambda = 707$ nm; interestingly, this emission peak is absent in the reduced form.²¹⁷ This phenomenon can be utilized for the detection of any biomolecule or enzyme activity able to oxidize or reduce the Os complex. For example, glucose can be catalyzed by glucose oxidase (GOx) to D-glucono-1,5-lactone and hydrogen peroxide. By coupling the activity of GOx and horseradish peroxidase (HRP), micromolar amounts of glucose can be detected. Initially, glucose is oxidized to D-glucono-1,5-lactone and O₂ reduced to H₂O₂. In the presence of small concentrations of H₂O₂, HRP catalyzes the oxidation of the

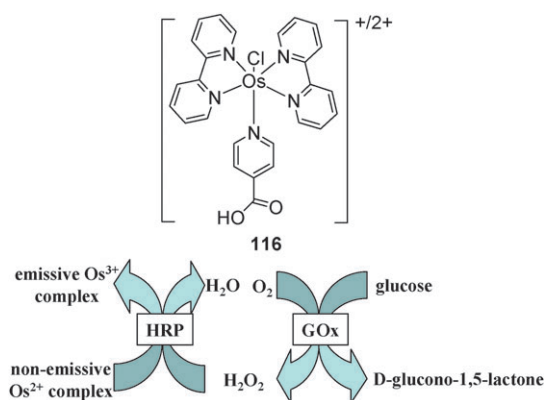


Fig. 23 Paradigm of detection of biocatalytic process able to oxidize or reduce the Os complex **116**.

Os complex, which changes from the reduced nonfluorescent state to the oxidized fluorescent state (see Fig. 23) and thereby realizes the detection of glucose.

10. Conclusions and outlook

We have presented the general design principles for phosphorescent chemosensors based on heavy-metal complexes and summarized recent advances in the detection of metal cations, anions, pH, oxygen, volatile organic compounds and biomolecules developed in our research group and in other groups. Compared with chemosensors based on purely organic luminophores, the reported examples of phosphorescent chemosensors are relatively few. However, this research field is attracting increasing attention and more and more novel phosphorescent chemosensors have been reported in recent years.

Considering the advantages and problems of present phosphorescent chemosensors, several future directions in this field should be followed to develop excellent phosphorescent chemosensors and exploit their further application:

(i) To exploit new design principles for phosphorescent chemosensors will be the first research direction in order to improve sensing performance.

(ii) Although the luminescent quantum efficiencies of phosphorescent heavy-metal complexes in degassed solution are high, they are decreased significantly when exposed to air due to the sensitivity of phosphorescence to oxygen. As a result, the quantum efficiencies of most heavy-metal complexes are much lower than most of fluorescent organic compounds, which can influence the detection sensitivity. Design and synthesis of phosphorescent complexes with sufficiently high quantum efficiencies in aerated solution is very important.

(iii) For actual application of phosphorescent chemosensors, especially for chemosensors for metal cations, pH and biomolecules, water solubility is very essential. However, the number of reported water-soluble phosphorescent chemosensors with excellent detection performance are very few. This will be another important research direction.

(iv) Compared with fluorescent organic compounds, the long lifetime of phosphorescence can eliminate the interference from the short-lived background fluorescence by using a

time-resolved luminescence technology, leading to the improved signal-to-noise ratio. Park's recent work successfully demonstrated the advantages of a long-lived phosphorescent signal over a short-lived fluorescent signal in enhancing the signal-to-noise ratio for a phosphorescent chemosensor.¹⁴² Design and synthesis of phosphorescent complexes with relatively long lifetimes for application in time-resolved luminescence detection will attract more and more research interest.

(v) Although many excellent phosphorescent chemosensors have been realized in solution, to design ratiometric or turn-on phosphorescent chemosensors and chemodosimeters as probes for monitoring special molecules in living cells and small animals is very important. Up to now, only very few such examples have been reported for cell imaging. Application in bioimaging *in vitro* and *in vivo* will be a very promising direction for phosphorescent chemosensors.

(vi) Multifunctionalization of phosphorescent complexes will attract increasing research interest. Combination of nanotechnology, heavy-metal complexes as phosphorescent units can be developed to fabricate novel multifunctional nanoparticles with photoluminescent, magnetic and radioactive properties.

In summary, the rich choice of ligand structures and metal centers makes the design of phosphorescent sensors relatively easy. It is expected that more and more excellent phosphorescent sensors will be developed in the years to come.

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