Fluorescent Chemosensors for Chromium(III) Ions and the Cr^{3+}/Cr^{2+} Ratio

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The shielded linear trisphenanthroline **1** is utilized as a triple reassurance probe and as an ON–OFF–ON signaling unit (after addition of Cu^{2+}) for the detection and quantification of Cr^{3+} ions. The analogous monophenanthroline **2** served as a ratiometric fluorescent chemosensor for analyzing the Cr^{3+}/Cr^{2+} ratio.

Highly selective cation or anion sensing, often based on fluorescence detection,[1] is crucial for many fields of technology, including biological, clinical, environmental, and waste management applications. Selective sensing protocols are in particular interesting for heavy transition-metal ions due to their high toxicity and crucial role in biological systems. While fluorescent probes for Zn^{2+}, Cu^{2+}, Hg^{2+} ions, etc.[2] are prevailing, very few have been reported for Cr^{3+},[3] despite the fact that the Cr^{3+} ion, an essential trace element in human nutrition, has great impact on the metabolism of carbohydrates, lipids, proteins, and nucleic acids.[4] On the other hand, chromium is an environmental pollutant, and its build-up due to various industrial and agricultural activities is a matter of great concern.[5] Herein, we will demonstrate that shielded phenanthrolines with three or one binding sites, such as **1** and **2** (Chart 1), are not only of use for the luminescence-based OFF–ON detection and quantitative determination of Cr^{3+} ions, but equally to resolve the mole fraction in a Cr^{3+}/Cr^{2+} mixture.

Tor,[6] Klemm,[7] and others[8] have demonstrated cogently that 1,10-phenanthrolines exhibit red-shifted luminescence upon extention along the 3,8-positions and may serve as tunable fluorophores upon addition of cations to the bisimine binding site. Thus, 3,8-extended oligophenanthrolines are foreseen to operate as versatile multiion fluorescence probes, but in the presence of metal ions unfortunately will give rise to an ill-defined mixture of homoleptic complexes. Over the years, we have developed phenanthrolines along the HETPHEN design

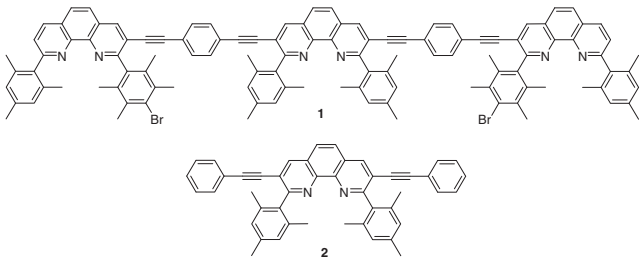

Chart 1. Model compounds of the present study.

that do not form bis- or trishomoleptic metal phenanthroline complexes[9] due to a sufficient steric shielding of the bisimine coordination site,[10] culminating in the development of a linear trisphenanthroline serving as an AND–NOR–OR logic circuit with H^+ as input and luminescence as output signal.[11] These findings encouraged us to investigate the ability of phenanthrolines **1** and **2** to act as luminescence probes for other ions as well.

Preparation of compound **1** was accomplished along a previous report from our group.[12] **1** was found to be highly fluorescent in nature ($\Phi_{Fl} \approx 0.79$) exhibiting sub-nanosecond fluorescence lifetimes (0.75 ± 0.05 ns). Although we have not yet fine-tuned the aryl groups at the three binding sites for additional selectivity in ion recognition, **1** already exhibits a remarkable selectivity in terms of emission response toward Cr^{3+} as compared to other metal ions, such as Li^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Ni^{2+}, Co^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, and Hg^{2+} (Supporting Information (SI): S2 and S5–S10). Interestingly, the λ_{max} of emission was shifted bathochromically by 115 nm upon addition of Cr^{3+}. In order to understand this interesting phenomenon, we have studied the luminescence behavior of **1** upon addition of Cr^{3+} (SI: S3). With increasing Cr^{3+} concentration, there was initially a steady quenching of the fluorescence at 413 nm, followed later by appearance of a new emission band at 528 nm. After addition of ca. 4.0 equivalents of Cr^{3+} the new emission band came to a saturation limit, with no further enhancement of the emission intensity being observable. After triple loading (see Job's plot, S15), the fluorescence lifetime of **1** increased to 2.4 (± 0.05) ns. The emission changes were readily recognized by the naked eye upon exposure of the solutions to a UV–vis lamp. The binding constant of **1** with Cr^{3+} was determined from UV–vis absorption titration ($\log K_1 = 6.9 \pm 0.1$, $\log \beta_2 = 12.9 \pm 0.1$, and $\log \beta_3 = 18.7 \pm 0.1$) in CH_2Cl_2–MeOH (4:1). Due to the three binding sites, altogether six different species may be present after addition of <3.0 equivalents of Cr^{3+}: uncoordinated **1**, two monoloaded species **1**, two doubly loaded species **1**, and the triply loaded **1**, all being in equilibrium (SI: S14).

1 experiences a strong fluorescence quenching when the binding sites are partly loaded, requiring an explanation. From earlier observations it seems plausible that partial loadings set up an efficient intraligand charge-transfer state (ILCT) from the phenylethynyl (p-e) unit to the loaded phenanthroline binding site.[11] While **1** is strongly luminescent, partial loading such as in $[\mathbf{1}(Cr)]^{3+}$ and $[\mathbf{1}(Cr)_2]^{6+}$ leads to quenching of the fluorescence at 413 nm. In contrast, the fully loaded ligand $[\mathbf{1}(Cr)_3]^{9+}$, lacks a strong dipole moment along the axis of the molecule, so that the dominating emitting state is now localized on the

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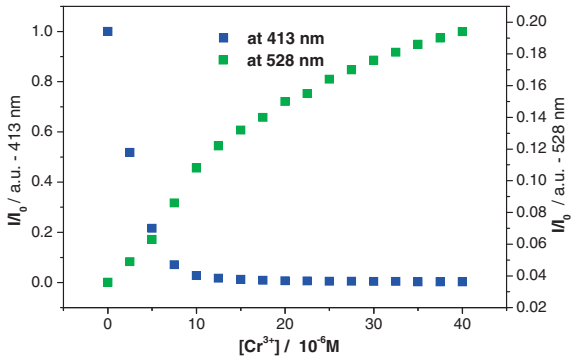

Figure 1. The emission response of **1** (1.0×10^{-5} M) in CH_2Cl_2–MeOH (4:1) upon successive addition of Cr^{3+} at two different wavelengths at rt.

individual phenanthroline units that are unsymmetrically loaded to account for the large bathochromic shift.[13] The emission at 528 nm only appears if all three sites are loaded, so that probe **1** has a built-in *triple reassurance* test for Cr^{3+} ions. In comparison to a single site chemosensor, **1** thus probes triply for the presence of the analyte before providing the response signal. A final assignment of the emitting states, though, has to await the outcome of a detailed photophysical study.

Due to the triple-site loading mechanism of **1** we reasoned that the rapid decline of the luminescence at 413 nm and the gradually increasing emission at 528 nm toward the end of chromium ion addition would allow augmention of the dynamic range of the sensoric response. Observing the changes at the two different wavelengths (Figure 1), the emission changes can indeed be very successfully and reliably detected not only at high but also at very low concentrations of Cr^{3+} ions (SI: S4). Thus, a reliable quantification can easily be effected over two orders of magnitude (ca. 0.4–40 $\times 10^{-6}$ M).

While screening a variety of metal ions, we realized that the emission at 413 nm decreased somewhat in the presence of Na^+, Mg^{2+}, Ni^{2+}, and Cd^{2+} ions (SI: S2), whereas upon addition of Cu^{2+} ions it was completely quenched. The association constants of Cu^{2+} to **1**, as determined from UV–vis absorption titration ($\log K_1 = 4.8 \pm 0.1$, $\log \beta_2 = 8.7 \pm 0.2$, and $\log \beta_3 = 12.9 \pm 0.7$), proved to be significantly lower than those observed with Cr^{3+}, suggesting use of the overload displacement strategy[14] to build an OFF–ON light-up probe for chromium(III) ions. Indeed, when the highly fluorescent **1** (ON) was first loaded with 5 equiv of Cu^{2+} ions the emission at 413 nm was efficiently quenched (OFF), but upon addition of Cr^{3+} a diagnostic emission at 528 nm (Figure 2) emerged (ON). This emission reached a saturation limit at 3.0 equivalents of Cr^{3+}. A similar ON–OFF–ON response to Cr^{3+} ions was equally monitored in the presence of 50.0 equivalents of Cu^{2+} ions (SI: S5).

Different redox states in chromium, i.e., Cr^{3+} and Cr^{2+}, caused quite a distinct fluorescence behavior with phenanthroline **1**. Upon addition of Cr^{2+}, **1** showed a decrease in the emission at 413 nm along with a slight appearance of an emission at 550 nm, in contrast to Cr^{3+} exhibiting a strong emission at 528 nm (Figure 3; SI: S10). It thus seemed interesting to inquire whether **1** would operate as a ratiometric probe for chromium ions in different oxidation states. To the

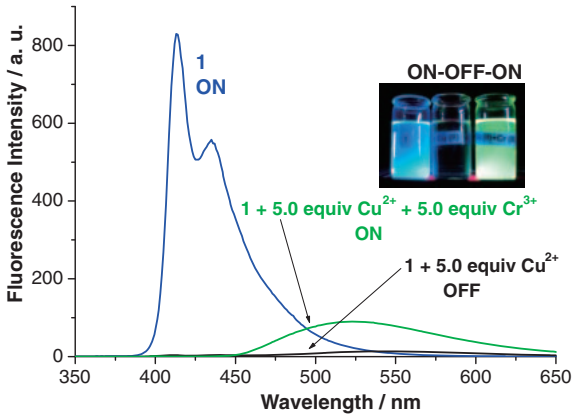

Figure 2. Emission spectra of **1** (1.0×10^{-5} M) and after addition of 5.0 equiv of Cu^{2+} ion followed by 5.0 equiv of Cr^{3+} ion in CH_2Cl_2–MeOH (4:1) at rt. Excitation wavelength: 400 nm. Inset: A visualization of the ON–OFF–ON probe.

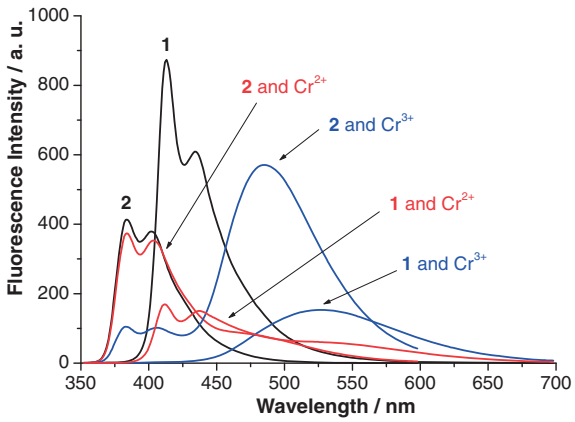

Figure 3. Emission spectra of **1** and **2** (1.0×10^{-5} M) in CH_2Cl_2–MeOH (4:1) at rt, in presence and absence of Cr^{3+} and Cr^{2+}.

best of our knowledge, there is no example of a luminescent chemosensor capable of quantifying the ratio of Cr^{3+} and Cr^{2+}.

Despite the different luminescence behavior of **1** toward the addition of chromium in different oxidation states we were unable to quantify the Cr^{3+}/Cr^{2+} ratio using a ratiometric analysis at the emission wavelengths 413 and 528 nm. We concluded that the failure was due to the involvement of three binding sites giving rise to complicated coordination scenarios with mixtures of Cr^{3+} and Cr^{2+} being attached to **1**. Thus, in order to reduce the number of coordinated species, we turned our attention to monophenanthroline **2**.[11]

2 shows a remarkable differential emission response toward Cr^{3+} as compared to that of other metal ions (SI: S11). Upon titration with Cr^{3+}, the emission at 384 nm decreased with concomitant appearance of a strong new band at 485 nm. Addition of Cr^{2+}, on the other hand, led to a faint decrease in the emission band at 384 nm with the appearance of a new band at 482 nm. The binding constants of **2** for Cr^{3+} ions, determined from UV–vis absorption titration ($\log K = 6.5 \pm 0.2$) were similar to the binding constants of **2** with Cr^{2+} ($\log K = 6.1 \pm 0.3$) (SI: S12 and S13).

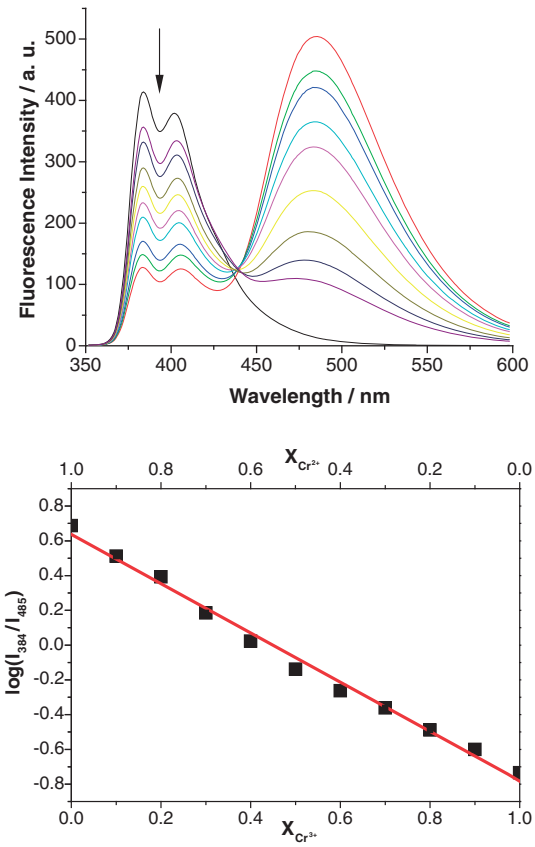

Figure 4. Top: Emission spectra of **2** (5.0×10^{-6} M) in the presence of various ratios of Cr^{3+} and Cr^{2+} (stepping up the mole fraction of Cr^{3+} and Cr^{2+} ions by 0.1 with each addition; total concentration of chromium salts: 5×10^{-6} M) in CH_2Cl_2–MeOH (4:1) at rt. Bottom: Linear correlation of the logarithm of the ratio I_{384}/I_{485} as a function of the mole fraction of Cr^{3+} and Cr^{2+} ions.

When different mole fractions of Cr^{3+} and Cr^{2+} were analyzed at a given total chromium concentration, significant changes of the emission intensity at 384 and 485 nm were observed. As a consequence, we used a luminescence titration (Figure 4, top) along with a ratiometric approach to determine the mole fraction. A linear dependence was established when the logarithm of the emission ratio at 384 and 485 nm was plotted as a function of mole fraction of Cr^{3+} and Cr^{2+}, allowing for a facile quantification (Figure 4, bottom).

In conclusion, we have demonstrated that **1** and **2** display a highly selective and ratiometric fluorescence response toward the addition of Cr^{3+}. In addition, **1** may be used as a *triple reassurance* probe with a large dynamic range and as OFF–ON light-up probe for chromium(III) ions[15] (in the presence of copper(II) ions). Monophenanthroline **2** operates as a ratiometric luminescent chemosensor for the quantification of Cr^{3+}/Cr^{2+} mixtures.

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Supporting Information

Characterization of **1** and **2**. UV–vis and luminescence spectra of **1** and **2** with different metal ions, titration experiments. This material is available free of charge on the web at: http://www.csj.jp/journals/bcsj/.

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