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A fluorescent molecular thermometer based on the nickel(II) high-spin/low-spin interconversion

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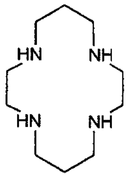
The temperature of a fluid can be measured through a variation of the fluorescence emission intensity of a naphthalene fragment covalently linked to a Ni^{II} tetraazamacrocyclic complex, which undergoes a temperature dependent spin interconversion equilibrium.

Luminescence is an easily detectable property which can be used to signal the occurrence of molecular events in real time and in real space. One of the first and most fascinating examples refers to the monitoring of the Ca^{2+} concentration inside the cell during muscle contraction by means of a specific chelating agent equipped with a fluorophore, using fluorescence microscopy as an investigating tool.[1] Since then, luminescent molecular receptors capable of sensing a variety of analytes (H^+,[2] s- and d-block metal ions,[3,4] anions,[5] amino acids)[6] have been developed. Most of them have been designed by following a two-component approach, *i.e.* by covalently linking a receptor subunit displaying selective affinity towards the envisaged substrate to a luminescent fragment.[7] Sensing is based on the occurrence of an intercomponent process (*e.g.* electron transfer) between the luminophore and the receptor, whose extent has to be distinctly different before and after recognition.

The success of the above outlined modular approach prompted us to the design of a two-component luminescent sensor of a physical rather than a chemical quantity: temperature. In the envisaged system, the luminescent fragment must be covalently linked to a bistable subunit, whose states A and B interact to a different extent with the nearby luminophore. Most importantly, the transition from A to B should be fast, reversible and controlled by temperature. We considered that the temperature dependent spin state interconversion of a transition metal centre could represent a convenient process to profit from, in order to build up a luminescent molecular thermometer. In particular, we looked at the high-spin/low-spin crossover of the Ni^{II} ion in a tetraaza coordinative environment like that offered by cyclam, **1**.[8]



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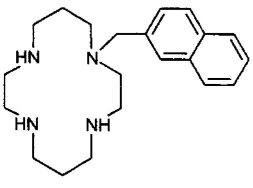

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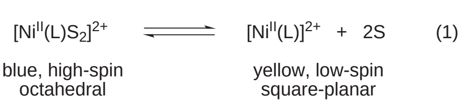
In this connection, we prepared a series of Ni^{II} complexes with the quadridentate macrocycle **2**, in which the naphthalene fluorescent fragment has been linked to the cyclam framework through a $–CH_2–$ spacer.† Complexes of formula $Ni^{II}(\mathbf{2})X_2$ were isolated as either yellow diamagnetic or blue–violet paramagnetic solids, depending upon the nature of the anion X^-. Poorly coordinating anions (ClO_4^-, $CF_3SO_3^-$) favour the formation of the yellow low-spin complexes, which have a square-planar stereochemistry. Anions of stronger coordinating tendencies (Cl^-, NCS^-, NO_3^-) stabilize the high-spin state, occupying the two apical positions of a slightly distorted octahedron. The stereochemical feature of high- and low-spin Ni^{II} complexes of cyclam and analogues have been ascertained through X-ray diffraction studies on a number of complexes.[9]

Spin-state and stereochemistry are maintained when the $Ni^{II}(\mathbf{2})X_2$ complexes are dissolved in non-coordinating solvents. When $X^- = ClO_4^-$, $CF_3SO_3^-$, a band at 470 nm (ε = 102 and 104 $dm^3\ mol^{-1}\ cm^{-1}$, respectively), typical for a low-spin square Ni^{II} tetramine complex is observed in $CHCl_3$ solution. Such a band is absent for $X^- = Cl^-$, NCS^-, NO_3^-, the less intense d–d bands of the high-spin form at 520 nm being observed. Very interestingly for sensing purposes, the two spin states exert a different influence on the emission properties of the proximate naphthalene subunit. In particular, the emission intensity in a $CHCl_3$ solution is remarkably higher for low-spin complexes (Quantum yield, Φ = 0.019 for ClO_4^-, 0.020 for $CF_3SO_3^-$) than for high-spin complexes (Φ = 0.009 for NO_3^-, 0.005 for NCS^-, 0.007 for Cl^-). Note that Φ values of the complexes are in any case substantially lower than that observed for plain naphthalene (Φ = 0.21 in ethanol). Transition metals typically quench the emission of a luminophore through two distinct mechanisms: electron transfer (eT) and energy transfer (*via* double electron exchange, ET). In particular, when the luminescent fragment is linked to a nitrogen atom of cyclam through a $–CH_2–$ spacer, the Ni^{II} centre tends to quench fluorescence through an ET mechanism.[10] This has been confirmed in the present work by the fact that when a solution of a $Ni^{II}(\mathbf{2})X_2$ complex in the glass forming butyronitrile solvent is brought to liquid nitrogen temperature, fluorescence is not revived at all, a behaviour suggestive of the occurrence of a double electron exchange.[11]

The ET based quenching mechanism involves the circular motion of electrons between the MO levels of the photo-excited fluorophore and the partially filled d orbitals of the Ni^{II} centre. The energy sequence of the latter orbitals changes with the metal spin-state and stereochemistry and this may affect the feasibility and rate of the double electron exchange process, thus determining a different quenching efficiency. The intimate details of the quenching mechanism have not been defined at this stage of the investigation. However, it is important to note that the considered two-component system contains a control subunit capable of existing in two states of comparable stability, which affect to a different extent the emission of the nearby covalently linked fluorescent fragment.

Ni^{II} complexes of cyclam and cyclam-like macrocycles in coordinating solvents like water and MeCN give an equilibrium mixture of the high- and low-spin forms.[8] In solution, the apical sites of the octahedral complex are occupied by two solvent molecules, S. The two species interconvert according to the following equilibrium:



$$\underset{\text{blue, high-spin octahedral}}{[Ni^{II}(L)S_2]^{2+}} \rightleftharpoons \underset{\text{yellow, low-spin square-planar}}{[Ni^{II}(L)]^{2+}} + 2S \qquad (1)$$

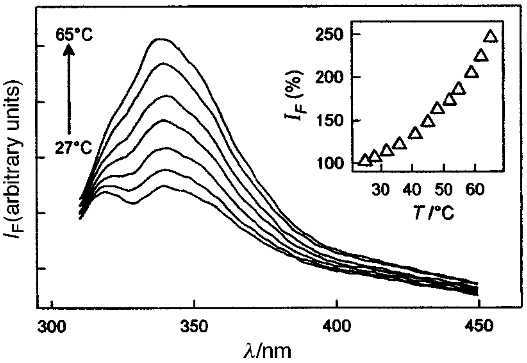


Fig. 1 Emission spectra of a 10^{-5} M MeCN solution of $[Ni^{II}(\mathbf{2})](ClO_4)_2$ recorded over the temperature range 27–65 °C (some spectra are omitted for clarity). I_F *vs.* temperature profile is shown in the inset.

The constant associated to the equilibrium (1) can be evaluated through the absorbance of the yellow form.[8] For a 10^{-3} M MeCN solution of $[Ni^{II}(\mathbf{2})](ClO_4)_2$, at 25 °C, $K = 4 \times 10^{-1}$: thus, the low-spin species is present at 30% and the high-spin species at 70%. The high-spin→low-spin conversion is typically endothermic, *i.e.* a temperature increase favours the formation of the yellow form. For a concentration $c \geqslant 10^{-3}$ M, this effect can be followed through an increase of the intensity of the d–d absorption band at 470 nm. In a very diluted concentration scale ($10^{-5} \leqslant c \leqslant 10^{-7}$ M), the temperature effect can be monitored through I_F, the intensity of the emission band of the naphthalene fragment: in particular, the temperature increase makes I_F increase appreciably.

Fig. 1 displays the emission spectra of an MeCN solution 10^{-5} M in $[Ni^{II}(\mathbf{2})](ClO_4)_2$ recorded over the temperature range 27–65 °C. The inset displays the corresponding I_F, *vs.* temperature profile. When decreasing temperature, I_F quickly decreases following the same profile. Thus, the $[NI^{II}(\mathbf{2})]^{2+}$ complex can be considered as a thermometric probe operating at the molecular level, and the I_F *vs.* T profile of the inset of Fig. 1 provides its calibration curve. Owing to the hydrophobic nature of the naphthyl substituent, $[Ni^{II}(\mathbf{2})](ClO_4)_2$ is not soluble in water even at a concenration as low as 10^{-7} M. It is soluble, however, in water–MeCN (20:80 v/v) and water–dioxane (50:50 v/v) mixtures, where it displays a similar temperature dependent emission behaviour over the temperature intervals 25–70 and 25–75 °C, respectively.

Other luminescent systems whose emission varies with temperature have been previously reported. In contrast to what is observed in the present study, in most cases a temperature increase depresses luminescence.[12] In these systems, there exists a non-emitting state, NR, slightly higher in energy than the S_1 emitting state. A temperature increase populates the NR state, which undergoes non-radiative decay, thus causing a decrease of the luminescence intensity. An increase of the emission intensity with increasing temperature was observed in the case of 'delayed fluorescence' displayed by some luminescent molecules (*e.g.* eosin).[13]

Light-emitting systems whose emission intensity varies with temperature can be used as probes for spatially and temporally resolved temperature measurement in any fluid including those of biological interest. Lipophilic fluorescent molecules displaying a decreasing emission with increasing temperature were proposed as optical thermometers of cell membranes.[14]

The two-component approach described here and the use of a metal containing a magnetically bistable subunit like $[Ni^{II}(cyclam)]^{2+}$ appears especially versatile for the construction of a fluorescent thermometer, used at a non-invasive concentration level. Thanks to the modular nature of the system, the fluorophore can be replaced at will, for instance to impart solubility in water or to provide emission in the desired wavelength interval, provided that an efficient energy transfer mechanism keeps operating.

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Notes and references

† **2**: cyclam **1** (2 g, 0.01 mol) was dissolved in hot toluene (100 mL) and 2-bromomethylnaphthalene (0.442 g, 0.002 mol) dissolved in the minimum amount of toluene added. The resulting solution was refluxed for 6 h and then cooled to room temp. The ammonium salts and the excess cyclam were filtered off and the resulting clear solution washed with 5% aqueous NaOH (3 × 25 mL) and water (2 × 25 mL). After drying over $MgSO_4$, toluene was distilled off to give compound **2** as a pale yellow oil; yield 61%. MS (ESI): 341 $[M + H^+]$. The NMR spectrum was in accord with the proposed structure.

$[Ni(\mathbf{2})](CF_3SO_3)_2$: a solution of **2** (0.34 g, 1 mmol) in toluene (10 mL) was heated at reflux and a solution of $Ni(CF_3SO_3)_2$ (0.36 g, 1 mmol) in ethanol (10 mL) was added. After refluxing for 1 h, the solution was cooled to room temperature and concentrated at the rotary evaporator. The orange–yellow precipitate was filtered and washed with diethyl ether; yield 92%. MS (ESI): 547 $[M - CF_3SO_3]$. Correct elemental analysis (C, H, N). The other Ni^{II} complexes were obtained by a similar method.

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