Controllable Intramolecular Motions That Generate Fluorescent Signals for a Metal Scorpionate Complex

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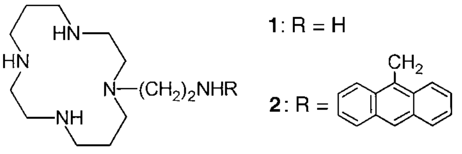
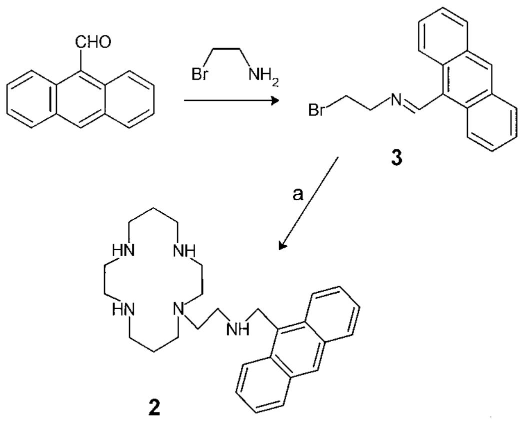
Molecular systems exist which contain a movable part, whose position can be varied through an external stimulus (addition of ions, change of the redox potential, illumination). Recent examples from supramolecular chemistry include rotaxanes of the π-donor-acceptor type, whose wheel can shuttle between two different stations following either a chemical or electrochemical command,[1] and copper-complexed catenates in which the Cu^I/Cu^{II} redox change triggers a half-turn of one of the rings.[2, 3] Systems of this type can be considered as elementary machines and are promising tools for information processing and storage at a molecular level.[4] The association of quick and reversible molecular movement with the generation of a distinct signal appears to be a useful step along this route.

We report here a multicomponent, covalently linked molecular system whose movable part contains a light-emitting fragment and can be reversibly relocated to one of two topologically definite positions by changing the pH value. The appended lumophore is quenched in only one of the positions. Therefore, the pH-driven intramolecular motion is signalled (and visually perceived) through quenching or revival of the light emission.

The basic system is the nickel(II) complex of a 14-membered tetraaza macrocycle bearing an alkylamine side chain (**1**). Compounds of this type combine the rigidity and inertness of the metal-bound macrocyclic ring with the flexibility and lability of the pendant arm.[5] In acidic solution, the protonated alkylamine side chain is forced away from the ring due to electrostatic repulsive effects; on increasing the pH value, the exocyclic nitrogen atom is deprotonated and coordinates to the metal center in an axial position. This reversible molecular motion can be followed both visually and spectrophotometrically: The protonated metal complex is yellow ($\lambda = 450$ nm; square planar, low spin), whereas the deprotonated form is blue-violet (d–d bands at $\lambda = 350$ and 525 nm in the visible region; octahedral, high spin). Functionalized macrocycles of type **1** are called scorpionands (or scorpiands), based on the analogy of an aggressive molecular "tail" that "stings" the chelated metal center from the top.[6] On varying the pH over a narrow interval ($pK_A \pm 1$), the side chain swings reversibly from one location to the other.



An anthracene fragment was appended through a methylene group to the scorpionand ethylamine side chain to give **2** (Scheme 1). Compound **2** will be indicated as B-L-An in the following discussion, where B denotes the macrocycle, L the alkylamine side chain, and An the fluorophore. Spectrofluorimetric titrations in $MeCN/H_2O$ (4/1) show a two-step behavior (Figure 1). First, the protonated form displays its maximum fluorescence. On addition of one equivalent of OH^- the fluorescence intensity I_F is quenched to 60%. Addition of a further equivalent of base completely quenches the fluorescence of the anthracene fragment. Fluorescence is revived to 60 and 100% on stepwise addition of two equivalents of acid.



Scheme 1. Synthesis of **2**: a) 1. cyclam (excess); 2. $NaBH_4$.

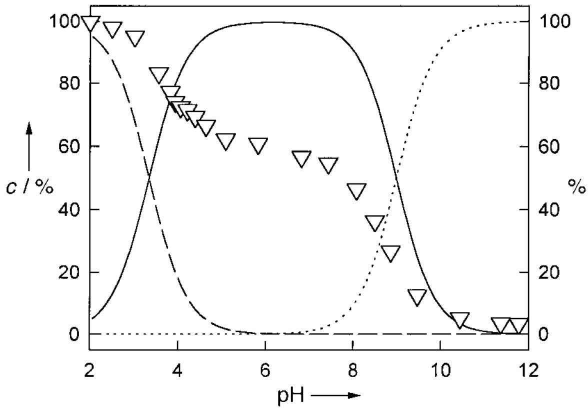


Figure 1. Distribution curves of the three Ni^{II} complexes of **2** (see Scheme 2; **A** dashed line, **B** solid line; **C** dotted line) in $MeCN/H_2O$ (4/1) and pH dependence of the fluorescence intensity I_F of the same solution (▽).

Nonlinear least-squares analysis of the potentiometric titration data indicated that three species were present in equilibrium in the pH range of 2–12. The species present in the strongly acidic region ($pH \leq 2$) displays an absorption band centerd at 460 nm, which is typical for a square-planar low-spin Ni^{II} species. This indicates that the amine side chain is protonated and does not coordinate to the metal center (this

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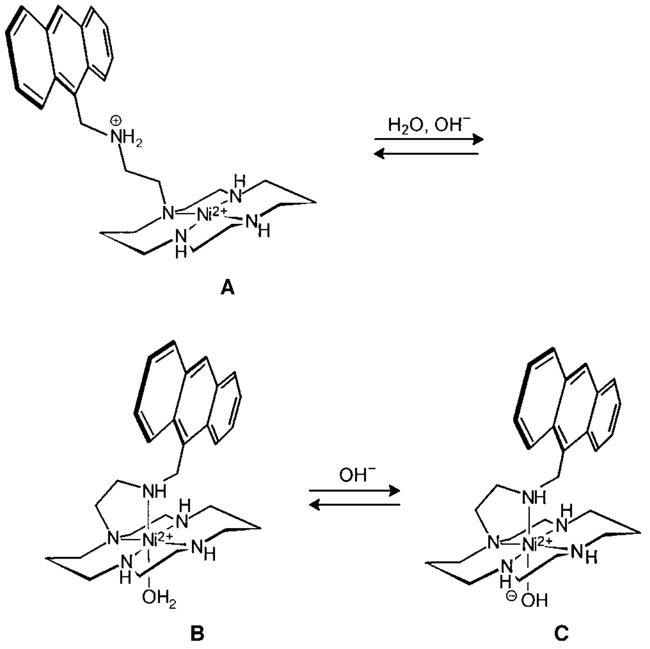
species is indicated as [Ni^{II}(B-LH$^+$-An)]$^{3+}$). Above pH 3 a proton is released, the band at 460 nm disappears, and a new band centered at 530 nm develops. This band is typically observed for an octahedral high-spin Ni^{II} complex (the band expected at 350 nm is hidden by the strong absorption by the An moiety). This indicates that above pH 3 the ethyl ammonium side chain is deprotonated and coordinates apically to the metal center; at the same time a water molecule coordinates to the opposite axial position to complete the octahedral arrangement. [Ni^{II}(B-L-An)(H$_2$O)]$^{2+}$ is present as the major species between pH 4 and 8. It is noteworthy that, due to the favorable contribution of the metal–ligand interaction, the pK_{A1} value for the deprotonation of the alkylammonium side chain in [Ni^{II}(B-LH$^+$-An)]$^{3+}$ (3.34 ± 0.02) is drastically lower than that observed for the reference system propyl(anthracen-9-ylmethyl)amine ($AnCH_2NHC_3H_7$, p$K_A = 8.91 \pm 0.02$) measured under the same conditions. A further deprotonation takes place at higher pH (p$K_{A2} = 8.99 \pm 0.02$). No variations are observed in the d–d absorption spectrum, and it is suggested that the proton is released from the axially bound water molecule to give [Ni^{II}(B-L-An)(OH)]$^+$. Above pH 10 this is the only species present. The stereochemical aspects of the three-component equilibrium are sketched in Scheme 2. The structures of the three species have been drawn based on semi-empirical calculations (PM3-transition metals within the Spartan package).



Scheme 2. Protonation–deprotonation equilibrium of the scorpionate complex.

The results of the spectrofluorimetric titrations (I_F vs. pH) are given in the distribution diagram in Figure 1. At pH 2 or lower, [Ni^{II}(B-LH$^+$-An)]$^{3+}$ displays its maximum emission.[7] The measured I_F value is ten times lower than that observed for the reference system $AnCH_2NH_2^+C_3H_7$ in the same medium. The lower emission has probably to be ascribed to the presence of the linked Ni^{II} center: Occasional folding of the aliphatic linker may bring the fluorophore and the metal within the van der Waals contact distance, causing a substantial quenching of the excited fluorophore.[8] Above pH 4, the pendant arm is deprotonated and swings onto the metal center to give [Ni^{II}(B-L-An)(H$_2$O)]$^{2+}$. This process is accompanied by partial fluorescence quenching: The intensity I_F is reduced to 60 % of that measured in acidic solution.

The nature of the quenching process operating in both [Ni^{II}(B-LH$^+$-An)]$^{3+}$ and [Ni^{II}(B-L-An)(H$_2$O)]$^{2+}$ can be explained by spectrofluorimetric studies at 77 K. In particular, vitrified ethanolic solutions of [Ni^{II}(B-LH$^+$-An)]$^{3+}$ and [Ni^{II}-(B-L-An)(H$_2$O)]$^{2+}$ do not show any fluorescence enhancement, which suggests the occurrence of an energy transfer process. It should be noted that the Ni^{II} ion possesses low-energy half-filled d levels suitable for a double electron exchange energy transfer process. Furthermore, the occurrence of the occasional contact between Ni^{II} and the An* fragment is favored for [Ni^{II}(B-L-An)(H$_2$O)]$^{2+}$, in which the metal–fluorophore distance is distinctly smaller than in the protonated form [Ni^{II}(B-LH$^+$-An)]$^{3+}$. In particular, the distance between the Ni^{II} ion and the anthracene carbon atom connected to the linker, as calculated by molecular modeling, is 4.4 Å in [Ni^{II}(B-L-An)(H$_2$O)]$^{2+}$ and 7.7 Å in [Ni^{II}(B-LH$^+$-An)]$^{3+}$. This makes the occasional metal–fluorophore contact and occurrence of a double electron exchange more favorable in species B (Scheme 2) and accounts for a 60 % decrease in the I_F value.

At pH 10 or higher, the axially bound water molecule is deprotonated: This simple act causes complete quenching of An fluorescence.[9] Again, the nature of the quenching can be inferred from spectrofluorimetric studies at 77 K. In particular, on freezing an ethanolic solution of [Ni^{II}(B-L-An)-(OH)]$^+$ at this temperature, the fluorescence revives to the value observed for [Ni^{II}(B-L-An)(H$_2$O)]$^{2+}$ under the same conditions. This suggests that, at room temperature, an electron transfer (ET) process gives a significant additional contribution to the quenching of the photoexcited anthracene fragment.

The electron transfer may be due to either a Ni^{II} →*An or an An* →Ni^{II} process. Coordination by a tetraaza macrocycle and, in particular, by a scorpionand favors the oxidation of Ni^{II} to Ni^{III}, and additional quenching may be due to a Ni^{II} →An* ET process. The decrease in the electrical charge due to axial coordination of hydroxide may favor the access to the Ni^{III} state and promote the Ni^{II} →An* ET process. The occurrence of an An* →Ni^{II} ET process seems less probable, as a reduction from Ni^{II} to Ni^{I} would not profit from the decrease in electrical charge associated with hydroxide coordination. The high quenching efficiency observed for the [Ni^{II}(B-L-An)(OH)]$^+$ form therefore results from the contribution of energy and electron transfer mechanisms involving the metal center.

The metal scorpionate reported here is a multicomponent molecular system whose movable part (the alkylamine side chain) can be made to oscillate between the metal center and a more distant point by the varying an external parameter, the pH value. The relocation of the side chain above the plane of the macrocyclic ring is induced by an increase in pH and is signalled by the partial quenching of the fluorescence of the appended fluorophore. A further increase in pH does not influence the position of the side chain, but simply increases the quenching efficiency. Most of the previously reported fluorescence switches typically exhibit two states: on or off.[10, 11] Systems displaying multistage emission are more rare and include 2-naphthol[12] and a tin(IV) complex of a functionalized porphyrin.[13] Ligand **2** is a novel high/low/off fluorescence switch whose control has a mechanical nature.

Experimental Section

3: 2-Bromoethylamine was allowed to react with a stoichiometric amount of 9-anthracenecaraldehyde in CH_2Cl_2. The reaction mixture was dried over Na_2SO_4, filtered, and evaporated to dryness. The residue was recrystallized from *n*-hexane/diethyl ether (1/1); yield 45%. Correct C,H,N analysis.

2: Cyclam (0.48 g, 2.4 mmol) was disolved in hot toluene, and **3** (0.14 g, 0.45 mmol) added as a solid. The resulting solution was heated at reflux for 3 h and then cooled to room temperature. The ammonium salts of excess cyclam were removed by filtration, and the clear solution extracted with 0.1 M NaOH to separate the remaining cyclam. The dried organic layer was filtered and evaporated to dryness. The resulting yellow oily substance was dissolved in EtOH (20 mL) and reduced with excess $NaBH_4$. Compound **2** was obtained as a pale yellow oil; yield (based on **3**) 70%. MS (ESI): 434 [M+H$^+$]. The NMR spectra were consistent with the proposed structure.

$[Ni^{II}(\mathbf{2})](ClO_4)_2 \cdot H_2O$: **2** (150 mg, 0.35 mmol) was dissolved in EtOH (30 mL), and a stoichiometric amount of an aqueous solution of 0.55 M $Ni(ClO_4)_2$ added. The obtained mixture was heated at reflux for 2 h and then evaporated to dryness. The residue was recrystallized from water. $[Ni^{II}(\mathbf{2})](ClO_4)_2 \cdot H_2O$ was obtained as a pale brown solid; yield 63%. Correct C,H,N analysis; MS (ESI): 590 [$M - ClO_4$].

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[7] The quantum yield for $[Ni^{II}(B\text{-}LH^+\text{-}An)]^{3+}$ is 0.083 in EtOH (0.27 for plain anthracene).

[8] The isolated component $[Ni^{II}(cyclam)]^{2+}$ quenches the emission of the reference compound $AnCH_2NH_2^+C_3H_7$ in aqueous MeCN by a bimolecular process. Reduction of I_F to 10% requires the addition of 4500 equivalents of $[Ni^{II}(cyclam)]^{2+}$. This emphasizes the "chelate effect" exerted by the aliphatic linker, which favors the intramolecular metal–fluorophore collisions in $[Ni^{II}(B\text{-}LH^+\text{-}An)]^{3+}$.

[9] One of the referees made the hypothesis that at pH 10 or above, a species of the composition $[Ni^{II}(B\text{-}L\text{-}An)(OH)Ni^{II}(B\text{-}L\text{-}An)]^{3+}$ could form: In this dinuclear species each cyclam subunit coordinates to its metal in a *cis* fashion, and the hydroxo group bridges the two Ni^{II} centers. Although hydroxo-bridged complexes are often observed in transition metal complexes in basic solution, this possibility can be ruled out in the present case: Complete quenching of fluorescence requires the addition of 2 equiv of OH^-, whereas 1.5 equiv are needed for the formation of the dinuclear species $[Ni^{II}(B\text{-}L\text{-}An)(OH)Ni^{II}(B\text{-}L\text{-}An)]^{3+}$. Furthermore, $[Ni^{II}(B\text{-}L\text{-}An)(OH)Ni^{II}(B\text{-}L\text{-}An)]^{3+}$, when replacing $[Ni^{II}(B\text{-}L\text{-}An)(OH)]^+$, did not fit well with the potentiometric titration data.

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SIAM, a Novel NMR Experiment for the Determination of Homonuclear Coupling Constants**

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The most important NMR parameters for the determination of molecular conformations in solution are cross-relaxation rates and coupling constants.[1] With the help of empirical Karplus relations, vicinal coupling constants (^3J) yield information about dihedral angles. For example, in peptides and proteins the $^3J(H^N,H^\alpha)$ coupling is related to the backbone angle ϕ.[2] However, the quantitative determination of coupling constants is difficult if the line width is not significantly smaller than the coupling constants of interest (Figure 1). In the case of in-phase doublets (e.g. in NOESY[3]

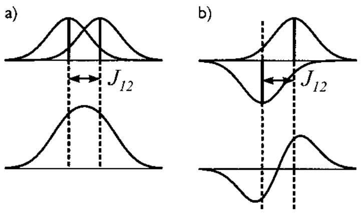

Figure 1. The apparent splittings of in-phase (a) and antiphase (b) doublets deviate markedly from the actual coupling constant J_{12} if the line width is not much smaller than J_{12}.[6] The individual doublet components are shown at the top and their superposition is shown at bottom. In this case the superimposed in-phase signal does not show any resolved splitting (a), whereas the apparent splitting of the superimposed antiphase signal is significantly larger than the coupling constant J_{12} (b).

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