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Lanthanide complexes of encapsulating ligands: Luminescent devices at the molecular level

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Abstract: Lanthanide complexes of encapsulating ligands are studied as luminescent devices at the molecular level. The photophysical properties of the complexes which, up till now, showed the most intense luminescence, are reported. The luminescence intensity of these complexes is discussed, considering the efficiency of incident light-emitted light conversion, defined as the product of the absorption efficiency and the luminescence quantum yield. It is illustrated, how the metal luminescence intensity can be enhanced by adapting the ligands on basis of previously obtained experimental results. The possible application of these complexes in fluoroimmunoassays is examined.

INTRODUCTION

The importance of the luminescence of lanthanide ions is related to its peculiar characteristics, e.g. long lifetime and line-like emission bands in the visible, which make these ions unique among the species that are known to luminesce. Because of these characteristics, lanthanide ions are widely used as luminescent species in non-molecular solids. In solution, application of complexes of lanthanide ions with conventional ligands is hindered by their kinetic lability.

Recent developments in the field of supramolecular chemistry have allowed the design of ligands capable of encapsulating lanthanide ions, thus forming kinetically inert complexes. By introduction of chromophoric groups in these ligands, an intense luminescence of the ion can be obtained via the "antenna effect" (Fig.1), defined as a light conversion process involving distinct absorbing (ligand) and emitting (metal ion) components. In such a process, the quantities that contribute to the luminescence intensity are (i) the efficiency of the absorption, (ii) the efficiency of the ligand-to-metal energy transfer, and (iii) the efficiency of the metal luminescence. Encapsulation of lanthanide ions with suitable ligands may therefore give rise to "molecular devices" capable to emit strong, long-lived luminescence (1).

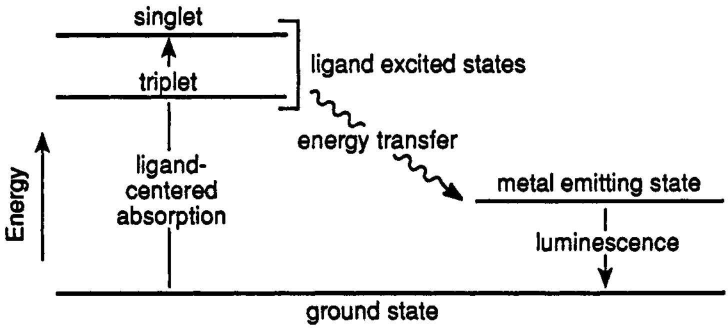


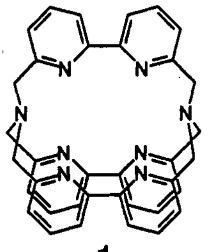
Fig. 1 Schematic representation of the "antenna effect" involving distinct absorbing (ligand) and emitting (metal ion) components.

Besides the intrinsic interest in their excited state properties, compounds of lanthanide ions, in particular of the Eu^{3+} and Tb^{3+} ions, are important for their potential use as luminescent labels for biological species in fluoroimmunoassays (FIAs) (1). This is most interesting because fluorimetric labelling represents an alternative method to the use of radioactive labels, which has long been the most common way of quantifying immunoreactions but still presents a number of drawbacks (2). The special interest of Eu^{3+} and Tb^{3+} compounds for FIAs is related to the long lifetimes of their emitting states which allow to enhance the sensitivity of the assays via time-resolved measurements (2). The first type of lanthanide complexes studied for application in FIAs are the Eu^{3+} chelates (2). These complexes are widely used in commercial kits, but the experimental procedure is complicated because of (i) the use of two different chelates (the first for complexation of the immunoreagent and the Eu^{3+} ion, and the second for fluorimetric detection of the Eu^{3+} ion), (ii) the insolubility of the luminescent chelate in water, which is the solvent of interest in FIA, and (iii) the need of protecting the chelated Eu^{3+} ion from interaction with the solvent. Research on lanthanide complexes with encapsulating ligands that incorporate chromophoric groups aims at simplified experimental procedures by taking advantage of the kinetic inertness, the shielding of the metal ion, and the intense luminescence of these complexes.

In this article we report on classes of lanthanide complexes which contain the compounds that, up till now, gave the most intense luminescence. The luminescence intensity of these complexes will be discussed on basis of the efficiency of incident light-emitted light conversion, defined as the product of the absorption efficiency and the luminescence quantum yield.

CRYPTATES

The prototypes of cryptates are the Eu^{3+} and Tb^{3+} complexes of the macrobicyclic cryptand **1**, containing three 2,2'-bipyridine (bpy) units (3). These complexes resulted to be kinetically inert in water. They showed strong absorption, but gave rather low luminescence quantum yields so that high values were not obtained for the efficiency of incident light-emitted light conversion (Table 1).



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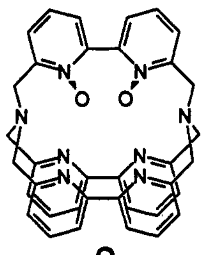

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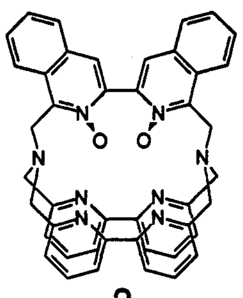

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The Eu^{3+} complexes of the ligands **2** and **3**, obtained upon substitution of one of the bpy's of the ligand **1** by a 2,2'-bipyridine-N,N'-dioxide ($bpyO_2$) or a 3,3'-biisoquinoline-N,N'-dioxide ($biqO_2$) unit, respectively, gave higher quantum yield values (4). These results were attributed to different efficiencies of the ligand-to-metal energy transfer and of the nonradiative decay processes (1,4). More exactly, it was proposed that the lowest ligand triplet excited state, which populates the Eu^{3+} $^5D_0$ emitting state, may compete more efficiently with the ligand-to-metal charge transfer (LMCT) states in the deactivation of the ligand singlet excited states because of the presence of $bpyO_2$ and $biqO_2$ localized excited states. The enhancement of the efficiency of the ligand-to-metal energy transfer was also ascribed to a closer approach between the ligand and the metal ion thanks to the presence of N-oxide groups. As to the nonradiative decay processes, it was shown that deactivation of the Eu^{3+} $^5D_0$ emitting state by O-H oscillators is less efficient because the ion is better protected from interaction with water than in the $[Eu(\mathbf{1})]^{3+}$ complex. The data reported in Table 1 show that the efficiencies of incident light-emitted light conversion for the $[Eu(\mathbf{2})]^{3+}$ and $[Eu(\mathbf{3})]^{3+}$ complexes are much higher than for the prototypes, thanks to the higher luminescence quantum yields and the similar absorption efficiencies.

TABLE 1. Efficiency of the incident light-emitted light conversion[a]

Compound	Absorption efficiency[b] × 10^2	Luminescence quantum yield × 10^2	Overall efficiency × 10^2
$[Eu(\mathbf{1})]^{3+c}$	6.2	2	0.12
$[Tb(\mathbf{1})]^{3+c}$	6.5	3	0.20
$[Eu(\mathbf{2})]^{3+c}$	4.5	15	0.68
$[Tb(\mathbf{7})]^{3+d}$	6.5	12	0.78
$[Eu(\mathbf{4})]^{3+c}$	8	10	0.80
$[Eu(\mathbf{3})]^{3+c}$	4.5	20	0.90
$[Eu(\mathbf{10})]^{3+d}$	8.7	15	1.30
$[Tb(\mathbf{5})]^{3+c}$	4.6	37	1.70

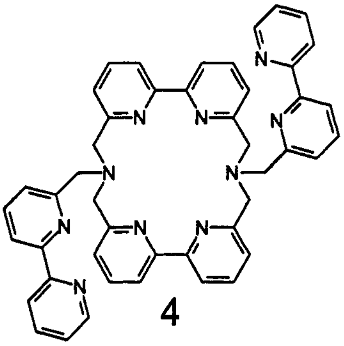
[a] Evaluated for 1.0×10^{-6} M solutions and 1 cm optical length. [b] Evaluated in correspondence with the λ_{max} values. [c] Data from Ref.1. [d] Obtained from the experimental data shown in Table 2.

COMPLEXES OF BRANCHED MACROCYCLIC LIGANDS

This class of complexes is characterized by the presence of two different types of ligands. Ligands of the first type contain the bpy·bpy macrocycle, as in ligand **4**, which (i) incorporates chromophoric units, (ii) encloses the metal ion, and (iii) acts as structural unit for the introduction of different types of branches. Ligands of the second type incorporate the triazacyclononane, as in ligand **5**, which is used as structural unit for carrying three bpy's in close proximity.

As to the first type of ligands, 2,2'-bipyridines and derivatives (1,5), 1,10-phenanthrolines (6), and phosphinate esters (7) have been introduced in the branches of the bpy·bpy macrocycle. Among the complexes of these ligands, the Eu^{3+} and Tb^{3+} complexes of the ligand **4** gave in water and methanol, respectively, the most intense luminescence. The efficiency of the incident light-emitted light conversion is high (Table 1) thanks to the high absorption efficiency and the good luminescence quantum yield (5). The Eu^{3+} and Tb^{3+} complexes of the ligand with two 9-methyl-1,10-phenanthrolines in the branches gave low luminescence intensity, in spite of the high absorption efficiency, because of the low luminescence quantum yield (6). On basis of the results obtained for the Eu^{3+} complex of the analogous ligand incorporating 6'-methyl-2,2'-bipyridines in the branches it was suggested that the luminescence intensity may be enhanced upon removal of the methyl groups (6). The Eu^{3+} and Tb^{3+} complexes of the ligand with two phosphinate esters in the branches gave also rather low luminescence intensities, in spite of the good luminescence quantum yields, because the presence of only two chromophores results in a low absorption efficiency (7). In order to enhance this quantity, introduction of chromophores in the phosphinate esters was suggested (7).

As to the second type of ligands, Eu^{3+} and Tb^{3+} complexes of the ligand **5** have first been investigated (8). They resulted to be kinetically inert in water. The $[Tb(\mathbf{5})]^{3+}$ complex gave a high luminescence quantum yield, while that of the $[Eu(\mathbf{5})]^{3+}$ complex was very low. The latter value was related to the presence of low-lying LMCT states involving the aliphatic nitrogens, which may efficiently deactivate both the excited states of the ligand and the Eu^{3+} $^5D_0$ emitting state. The $[Tb(\mathbf{5})]^{3+}$ value was related to the absence of low-lying excited states and the lack of thermally activated decay processes of the Tb^{3+} $^5D_4$ emitting state. Interestingly, the $[Tb(\mathbf{5})]^{3+}$ complex gave the highest efficiency of the incident light-emitted light conversion (Table 1). Recently, the triazacyclononane has been used as structural unit for carrying three 5,5'-substituted bipyridines (9). Preliminary results revealed that the Eu^{3+} and Tb^{3+} complexes of the new ligand are not stable in water. The Eu^{3+} complex gave a high quantum yield value in dehydrated acetonitrile.



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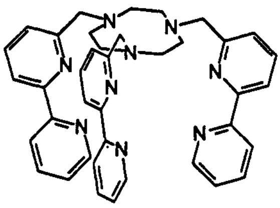

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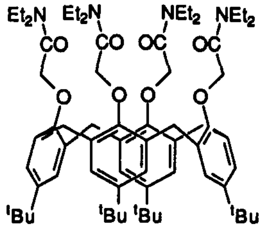
COMPLEXES OF CALIX[4]ARENES

Initially, the Eu^{3+} and Tb^{3+} complexes of the p-t-butylcalix[4]arene tetra-acetamide, ligand **6**, were studied (10). These complexes resulted to be kinetically inert in water and the ion was efficiently shielded from interaction with water molecules. The $[Tb(\mathbf{6})]^{3+}$ complex gave a high luminescence quantum yield, while that of the $[Eu(\mathbf{6})]^{3+}$ complex was very low (Table 2). The behavior of the latter complex was explained by the presence of low-lying LMCT states which may efficiently deactivate both the excited states of the ligand and the Eu^{3+} $^5D_0$ emitting state. The high value of the luminescence quantum yield of the $[Tb(\mathbf{6})]^{3+}$ complex was attributed to the lack of thermally activated decay processes of the Tb^{3+} $^5D_4$ emitting state and to the absence of low-lying excited states deactivating the ligand excited states. In spite of the high luminescence quantum yield, the efficiency of the incident light-emitted light conversion for this complex is low because of the low absorption efficiency.

Afterwards, in order to enhance the absorption efficiency, calix[4]arenes carrying bpy's as efficient chromophores have been studied (11). This approach implies the disadvantage of diminishing the complexation ability of the ligand because the bpy's have worse ligating properties than the amides. First, the ligands **7** and **8** were designed and synthesized (12). Solid samples of the lanthanide complexes of these ligands couldn't be isolated, but these complexes could be obtained in dehydrated acetonitrile solutions. A 1:1 stoichiometry and formation constants of the order of 10^5 M^{-1} resulted from the



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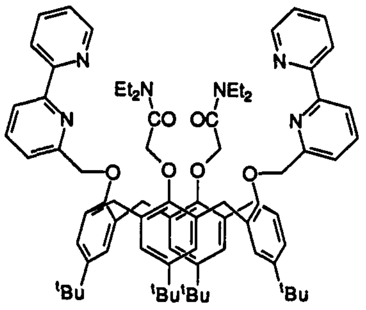

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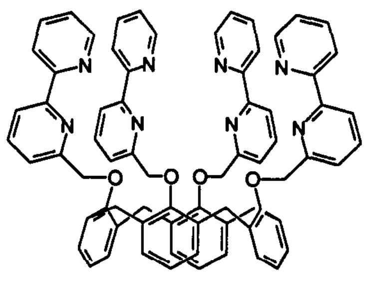

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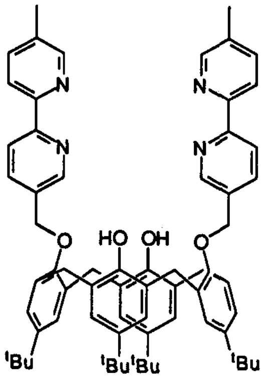

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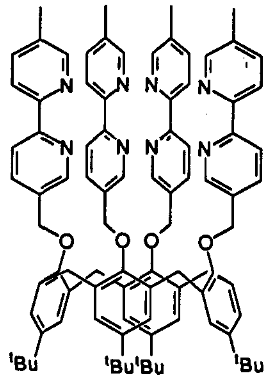

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photophysical measurements. The data of the Eu^{3+} and Tb^{3+} complexes of the ligands **7** and **8**, gathered in Table 2, were obtained in solutions where 90% of the ligands was complexed. The quantum yield values for the complexes of the ligand **7** are higher than those of the complexes of the ligand **8**. This behavior may be attributed to a weaker metal-ligand interaction in complexes of the ligand **8** because of the absence of strongly ligating amide groups and of the steric hindrance that the four bpy's may undergo when approaching the metal ion. It is worthwhile noting that the complexes of the ligand **8** exhibit very high values for the molar extinction coefficients, but the luminescence quantum yields are too low to obtain high luminescence intensities.

TABLE 2. Absorption and luminescence data[a]

Compound	Absorption		Lifetime[b]	Luminescence quantum yield[c]
	λ_{max} nm	ε_{max} $M^{-1}cm^{-1}$	τ ms	$\Phi \times 10^2$
$[Eu(\mathbf{6})]^{3+d}$	273	1100	0.65	0.02
$[Tb(\mathbf{6})]^{3+d}$	273	1100	1.5	20
$[Eu(\mathbf{7})]^{3+}$	305	28000	0.65	4
$[Tb(\mathbf{7})]^{3+}$	306	29000	1.9	12
$[Eu(\mathbf{8})]^{3+}$	307	50000	0.65	<1
$[Tb(\mathbf{8})]^{3+}$	305	46700	1.4	2
$[Eu(\mathbf{9})]^{3+}$	309	22500	1.2	3
$[Eu(\mathbf{10})]^{3+}$	305	39600	1.6	15

[a] In aerated acetonitrile solution at 300 K, unless otherwise noted. [b] Measured in correspondence with the emission bands $^5D_0 \rightarrow {}^7F_2$ and $^5D_4 \rightarrow {}^7F_5$ for Eu^{3+} and Tb^{3+}, respectively. [c] Excitation in ligand-centered bands. [d] In aerated water solution at 300 K; data from Ref.10.

In an attempt to improve the complexation ability of the ligand and the luminescence intensity of the ion, 5,5'-substituted bipyridines were attached to the p-t-butylcalix[4]arene instead of the 6-substituted bipyridines of the previously discussed ligands, and the ligands **9** and **10** were obtained (13). Interestingly, complexes of these ligands could be isolated (11), which suggests better complexation abilities than in the case of the ligands **7** and **8**. The Eu^{3+} complexes of the ligands **9** and **10** resulted kinetically inert in dehydrated acetonitrile where the photophysical data were obtained (Table 2). The lifetime and quantum yield values for the $[Eu(\mathbf{8})]^{3+}$ and $[Eu(\mathbf{10})]^{3+}$ complexes are in agreement with a stronger complexation ability of the ligand **10**. The molecular models show that in the ligand **10** the four bpy's undergo less steric hindrance when approaching the metal ion. Among the calixarene complexes, the most interesting results have been obtained for the $[Eu(\mathbf{10})]^{3+}$ complex, which has high molar extinction coefficients and a high luminescence quantum yield. The efficiency of the incident light-emitted light conversion is close to the highest value found up till now, which was obtained for the $[Tb(\mathbf{5})]^{3+}$ complex (Table 1).

CONCLUSIONS

We have illustrated how the metal luminescence intensity can be enhanced by adapting the ligands on basis of previously obtained experimental results. Moreover, it has been shown that design of luminescent molecular devices based on lanthanide complexes has to take into account both the absorption efficiency and the metal luminescence quantum yield upon ligand excitation, which is determined by the amount of ligand-metal interaction and by the effect of the ligand on the nonradiative deactivations of the metal emitting state.

As far as the use of these complexes as luminescent labels in FIA is concerned, it is necessary to take into account the effects that both the attachment of the label to the biological species and the serum medium may have on the chemical stability and the luminescence intensity of the complexes. Therefore, these aspects, in addition to the photophysical behavior of the luminescent complex, have to be studied.

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