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Synthesis, Characterization, and Photophysical Properties of Rare Earth Complexes of N-Phenyl-2-aminobenzoic Acid and 1,10-Phenanthroline

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Summary. Some novel binary and ternary complexes of rare earth ions (Gd, Eu, Tb) with N-phenyl-2-aminobenzoic acid and 1,10-phenanthroline were synthesized by homogenous precipitation and characterized by elemental analysis, IR spectra, UV/Vis spectra, and thermal analysis. The phosphorescence spectra and lifetimes of gadolinium complexes were measured, and the triplet state energies of N-phenyl-2-aminobenzoic acid and 1,10-phenanthroline as well as the energy transfer efficiencies between N-phenyl-2-aminobenzoic acid and 1,10-phenanthroline were determined. The photophysical properties such as luminescence and intramolecular energy transfer between the rare earth center ions and the ligands and between ligands are discussed.

Keywords. Complexes of Gd^{3+}, Eu^{3+}, and Tb^{3+}; Synthesis; Characterization; Photophysical properties; N-Phenyl-2-aminobenzoic acid; 1,10-Phenanthroline.

Synthese, Charakterisierung und photophysikalische Eigenschaften von Seltenerdkomplexen der N-Phenylanthranilsäure und des 1,10-Phenanthrolins

Zusammenfassung. Einige neue binäre und ternäre Komplexe von Seltenerdionen (Gd, Eu, Tb) mit N-Phenylanthranilsäure und 1,10-Phenanthrolin wurden durch homogene Fällung synthetisiert und durch Elementaranalyse, IR- und UV/Vis-Spektren und thermische Analyse charakterisiert. Die Phosphoreszenzspektren und Lebensdauern der Gadoliniumkomplexe wurden gemessen, und die Triplettenergien der N-Phenylanthranilsäure und des 1,10-Phenanthrolins sowie die Energietransfereffizienz zwischen den beiden wurden abgeleitet. Die photophysikalischen Eigenschaften wie Lumineszenz und intramolekularer Energietransfer zwischen Seltenerdion und Liganden sowie zwischen den Liganden werden diskutiert.

Introduction

In recent years, there has been a growing interest in the potential application of europium and terbium coordination compounds as luminescent materials and luminescent probes for a variety of chemical and biological studies [1, 2]. Con-

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siderable investigations focused on the luminescence properties, energy match, and energy transfer of rare earth chelates with β-diketones [3–5]. However, little attention has been paid to luminescent rare earth complexes with aromatic carboxylic acids [6]. Compared to the rare earth chelates with β-diketones, complexes with aromatic carboxylic acids offer the advantage of stability of the luminescent properties owing to their infinite chain structure [7, 8]. In this paper, a series of novel binary and ternary complexes of Gd^{3+}, Eu^{3+}, and Tb^{3+} with N-phenyl-2-aminobenzoic acid and 1,10-phenanthroline were synthesized by homogenous precipitation and characterized by elemental analysis, IR spectra, thermal analysis, and UV/Vis spectra. Gadolinium complexes were used as model complexes, and the triplet state energies of N-phenyl-2-aminobenzoic acid and 1,10-phenanthroline were determined. From the energy match assumption, the luminescence properties of the corresponding complexes of europium and terbium were studied. The intramolecular energy migration processes between the acid and Ln^{3+} and from N-phenyl-2-aminobenzoic acid to 1,10-phenanthroline are discussed.

Results and Discussion

The compositions of the complexes were confirmed on the basis of elemental analyses; the corresponding data are summarized in Table 1.

The IR spectra of the binary and ternary complexes differ from those of the free ligands (Table 2). In the rare earth complexes, the following bands present in the spectra of the free ligand are missing: ν(C=O) at 1657 cm^{-1} and ν(OH) at 2863.3,

Table 1. Compositions of the complexes (N-H*PA*: N-phenyl-2-aminobenzoic acid; *phen*: 1,10-phenanthroline; *RE* = rare earth)

	Found (%)				Calculated (%)			
	C	H	N	*RE*	C	H	N	*RE*
Gd(N-*PA*)$_3$·4H$_2$O	53.98	4.11	5.08	18.36	54.06	4.39	4.85	18.17
Eu(N-*PA*)$_3$·4H$_2$O	54.07	4.20	5.10	17.93	54.38	4.42	4.88	17.68
Tb(N-*PA*)$_3$·4H$_2$O	53.64	4.09	5.04	18.04	53.95	4.38	4.84	18.32
Gd(N-*PA*)$_3$·*phen*·2H$_2$O	60.13	3.94	6.68	15.17	60.60	4.16	6.93	15.57
Eu(N-*PA*)$_3$·*phen*·2H$_2$O	60.41	4.01	6.74	15.00	60.92	4.18	6.98	15.13
Tb(N-*PA*)$_3$·*phen*·2H$_2$O	60.13	3.99	6.74	15.47	60.50	4.15	6.92	15.71

Table 2. IR spectroscopic data

	Absorption bands/cm^{-1}					
N-*PA*	3333.6 m		1657.9 w	1409.7 s		1324.6 w
Na(N-*PA*)	3322.0 m	3039.7 w	1610.8 w	1386.0 s	224.8	1317.6 w
Eu(N-*PA*)$_3$·4H$_2$O	3308.9 m	3042.1 w	1609.0 w	1398.5 s	211.4	1318.3 w
Eu(N-*PA*)$_3$·*phen*·2H$_2$O	3309.4 m	3042.4 w	1612.1 w	1396.7 s	215.4	1316.2 w
Tb(N-*PA*)$_3$·4H$_2$O	3318.9 m	3041.9 w	1610.9 w	1397.1 s	213.8	1316.2 w
Tb(N-*PA*)$_3$·*phen*·2H$_2$O	3305.7 m	3040.5 w	1612.2 w	1398.5 s	213.7	1315.2 w
Band assignment	ν_s(NH)	ν_s(C-H)	ν_s(COO$^-$)	ν_{as}(COO$^-$)	$\Delta\nu$(COO$^-$)	ν(C-N-C)

2732.6, 2640.2, and 2567.9 cm^{-1}. The characteristic absorption band of NH appears both in complexes and ligand, indicating that the coordination of the rare earth ions with N-H*PA* proceeds *via* the oxygen atom of carboxyl group and not *via* the nitrogen atom of the amino group. Besides, the $\Delta\nu$ (ν_s–ν_{as}) value of COO^- of rare earth complexes is lower than that of the sodium salt of N-H*PA* (211.4, 215.4, 213.8, and 213.7 cm^{-1} *vs.* 224.8 cm^{-1}). This implies that to bidentate coordination takes place [8]. From the IR spectra of the ternary complexes, it can also be seen that the vibration frequency of 1650 cm^{-1} belonging to the phenyl ring of 1,10-phenanthroline becomes weaker than that of free *phen*. The out-of-plane bending vibrations of the hydrogen atoms on the phenyl ring of *phen* decrease from 855 and 740 cm^{-1} to 844 and 724 cm^{-1}, indicating that *phen* participates in the coordination.

When heated in air, the TG-DTA curves of Gd(III), Eu(III), and Tb(III) with N-H*PA* show two steps: The first one corresponds to the loss of crystal water and yields the anhydrous salts, accompanied by an endothermic effect; the second refers to the decomposition of the anhydrous complexes to the oxides Gd_2O_3, Eu_2O_3, and Tb_4O_7 and is accompanied by a strong exothermic effect. The oxides are stable in the temperature range of 1163–1273 K.

Figures 1 and 2 show the UV/Vis spectra of NaN-*PA*, Eu(*phen*)$_2$·Cl_3·$2H_2O$, Eu(N-*PA*)$_3$·$4H_2O$, Eu(N-*PA*)$_3$·*phen*·$2H_2O$ and NaN-*PA*, Tb(*phen*)$_2$·Cl_3·$2H_2O$, Tb(N-*PA*)$_3$·$4H_2O$, Tb(N-*PA*)$_3$·*phen*·$2H_2O$, respectively. The absorption peaks in the spectra of the complexes show a slight red shift, the shape and intensity of the peaks being basically similar to that for the free ligands. This implies that the absorption depends mainly on the ligand. Besides, in the spectra of Eu(N-*PA*)$_3$·*phen*·$2H_2O$ and Tb(N-*PA*)$_3$·*phen*·$2H_2O$ the characteristic absorption of N-*PA*

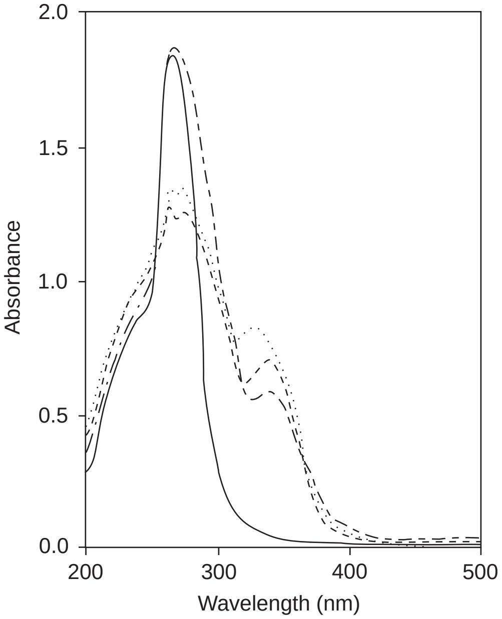

Fig. 1. UV/Vis spectra of NaN-*PA* (···), Eu(N-*PA*)$_3$·$4H_2O$ (– –), Eu(*phen*)$_2$·Cl_3·$2H_2O$ (—), and Eu(N-*PA*)$_3$·*phen*·$2H_2O$ (–·–)

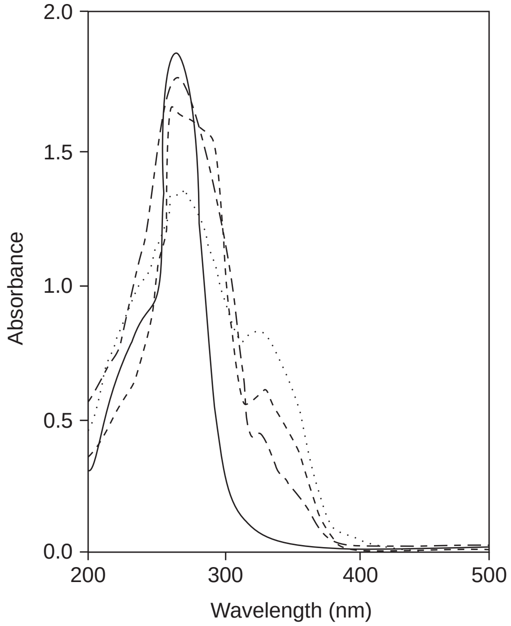

Fig. 2. UV/Vis spectra of NaN-*PA* (···), Tb(N-*PA*)$_3$·4H$_2$O (– –), Tb(*phen*)$_2$·Cl$_3$·2H$_2$O (—), and Tb(N-*PA*)$_3$·*phen*·2H$_2$O (–·–)

Table 3. Low temperature phosphorescence spectra and phosphorescence lifetimes (±10%)

	Gd(N-*PA*)$_3$·4H$_2$O	Gd(N-*PA*)$_3$·*phen*·2H$_2$O
Lowest triplet state energies (cm^{-1})	24330	–
$\Delta E(\mathrm{T}-{}^5\mathrm{D}_0)$ (cm^{-1})	7066	–
$\Delta E(\mathrm{T}-{}^5\mathrm{D}_4)$ (cm^{-1})	3830	–
Phosphorescence lifetimes (s)	3.0	2.1
Energy transfer efficiency (%)	–	30

(337 nm) can only be observed as a small peak overlapping with the spectrum of *phen*. Nevertheless, the characteristic absorption peak of *phen* (265 nm) is present. These phenomena suggest that for the differences in the absorption wavelengths and molecular absorbtion coefficients the energy transfer process from ligand to rare earth ion has to be accounted. In the binary complexes Eu(N-*PA*)$_3$·4H$_2$O and Tb(N-*PA*)$_3$·4H$_2$O, N-*PA* absorbs energy and transfers it to Eu^{3+} and Tb^{3+}, whereas in the ternary complexes Eu(N-*PA*)$_3$·*phen*·2H$_2$O and Tb(N-*PA*)$_3$·*phen*·2H$_2$O, *phen* absorbs energy and transfers it to the rare earth ion; the amount of energy absorbed by N-*PA* is very low in this case.

Gd^{3+} complexes were selected as model complexes for the determination of the triplet state energies of the organic ligands owing to their high phosphorescence-fluorescence ratios compared to those of other Ln^{3+} complexes. The phosphorescence spectra of Gd(N-*PA*)$_3$·4H$_2$O and Gd(N-*PA*)$_3$·*phen*·2H$_2$O were measured at 77 K in ethanol. The lowest triplet state energy was determined assigning the shortest wavelength of the phosphorescence band to the 0–0 transition. The energy differences between the triplet state of the ligands and the resonance energy levels of Eu^{3+} (^{5}D$_0$) and Tb^{3+} (^{5}D$_4$) ions were calculated. The results are summarized in

Table 3. From the energy differences ($\Delta E(\mathrm{Tr}\text{-}^5\mathrm{D_j})$, $\mathrm{j} = 0$ or 4) it can be seen that N-H*PA* can sensitize europium and terbium ions effectively. The lowest triplet energy position of N-H*PA* is more suitable for the excited energy level of Tb^{3+}; therefore it can be predicted that the fluorescence intensity of Tb^{3+} complexes would be stronger. According to the luminescence principle of rare earth complexes with organic ligands [4], the intramolecular energy transfer efficiency depends chiefly on two energy transfer processes [5]: the first one leads from the lowest triplet level of the ligands to the emissive energy level of the Ln^{3+} ion by *Dexter*'s resonant exchange interaction; the second one is just an inverse energy transfer by a thermal deactivation mechanism. Both energy transfer rate constants depend on the energy difference between the lowest triplet level energy of the ligands and the resonant emissive energy of Ln^{3+}.

Intramolecular energy transfer in rare earth complexes conforms to *Dexter*'s exchange energy transfer theory [9, 13]:

$$k_{\mathrm{ET}} = (2\pi Z^2/\mathrm{R}) \exp{(-2r/l)} \int F_{\mathrm{d}}(E) F_a(E) \mathrm{d}E \tag{1}$$

k_{ET} is the rate constant of energy transfer, r is the intermolecular distance between the energy donor and acceptor atoms, l is the *van der Waals* radius, the integral represents the overlap between the luminescence spectrum of the ligands and the absorption spectrum of Ln^{3+} ($F_{\mathrm{d}}(E)$: the luminescence spectrum of energy donor (ligand), $F_{\mathrm{a}}(E)$: absorption spectrum of energy acceptor (Ln^{3+}), and $2\pi Z^2/\mathrm{R}$ is a constant relating to the mutual distance between Ln^{3+} and coordinated atom. r and l are both considered to be constant for intramolecular energy transfer processes.

From Eq. (1), k_{ET} increases with decreasing energy difference $\Delta E(\mathrm{Tr}{-}Ln^{3+})$ between the triplet state energy of ligands and the resonance emission energy of Eu^{3+} and Tb^{3+}. Thus, ligands with a larger energy difference cannot sensitize rare earth ions effectively. On the other hand, there exists an inverse energy transfer process which affects luminescence intensity by temperature [10, 13] ($k(T)$: rate constant of inverse energy transfer process (thermal deactivation process), A: preexponential factor):

$$k(T) = A \exp(-\Delta E(\mathrm{Tr} - Ln^{3+})/\mathrm{R}T) \tag{2}$$

It can be seen that in the inverse energy transfer process the activation energy is approximately equal to $\Delta E(\mathrm{Tr}{-}Ln^{3+})$; therefore, a decreasing energy difference increases $k(T)$. Based on this evidence the conclusion can be drawn that $\Delta E(\mathrm{Tr}{-}Ln^{3+})$ is of opposite influence on the two energy transfer processes and an optimal value can be assumed to exist.

Many reports have indicated that the luminescence properties of ternary complexes of rare earth with carboxylic acids and *phen* change dramatically in contrast to those of the binary complexes [11]. Therefore we can guess that in ternary complexes systems *phen* will influence the luminescence intensity considerably. Figure 3 shows the phosphorescence spectra of $\mathrm{Gd(N\text{-}}PA)_3\cdot 4\mathrm{H_2O}$, $\mathrm{Gd(N\text{-}}PA)_3\cdot phen\cdot 2\mathrm{H_2O}$, and $\mathrm{Gd}(phen)_2\cdot \mathrm{Cl_3}\cdot 2\mathrm{H_2O}$, respectively. The phosphorescence spectrum of the ternary complex $\mathrm{Gd(N\text{-}}PA)_3\cdot phen\cdot 2\mathrm{H_2O}$ is similar to that of the binary complex $\mathrm{Gd}(phen)_2\cdot \mathrm{Cl_3}\cdot 2\mathrm{H_2O}$ but different from that of corresponding binary complex of N-H*PA*. Obviously, in Gd^{3+} ternary complexes *phen* is

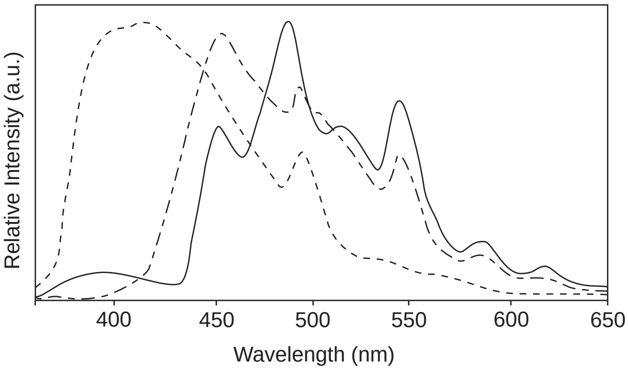

Fig. 3. Low temperature phosphorescence spectra of Gd(*phen*)$_2$·Cl$_3$·2H$_2$O (—; $\lambda_{ex} = 302.0$ nm), Gd(N-*PA*)$_3$·4H$_2$O (– –; $\lambda_{ex} = 318.7$ nm), and Gd(N-*PA*)$_3$·*phen*·2H$_2$O (–·–; $\lambda_{ex} = 307.6$ nm) in $5 \cdot 10^{-4}$ mol/l ethanol:*DMF* = 4:1 at 77 K

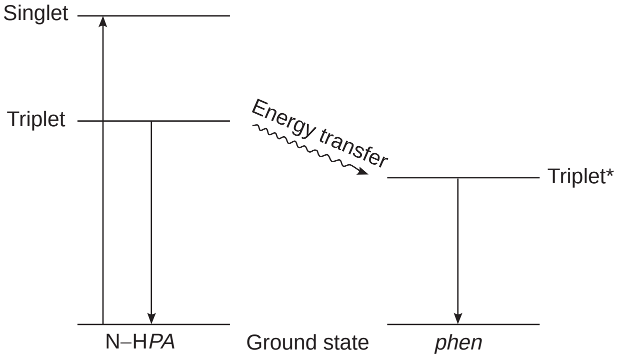

Fig. 4. Intramolecular energy transfer process from N-phenyl-2-aminobenzoic acid to 1,10-phenanthroline

main energy donor and predominantly sensitizes the Ln^{3+} ions luminescence. Besides, there exists an intramolecular energy migration from N-H*PA* to *phen*. In order to verify this assumption, the low temperature phosphorescence lifetimes of the complexes were determined, and the intramolecular energy transfer efficiency between aromatic carboxylic acid and *phen* were calculated (Table 3). The intramolecular energy transfer process can be described as sketched in Fig. 4 [12–14]. The energy transfer rate equation and the energy transfer efficiency equation can be represented as follows:

$$k^*_{\mathrm{ET}} = \tau_0^{-1} - \tau_1^{-1} \tag{3}$$

$$\eta_{\mathrm{ET}} = k^*_{\mathrm{ET}}(k^*_{\mathrm{ET}} + k_1)^{-1} \tag{4}$$

k^*_{ET} is the rate constant of energy transfer from N-*PA* to *phen*, k_1 is the rate constant of phosphorescence of the Gd^{3+} complex with N-*PA*, τ_0 and τ_1 are the phosphorescence lifetimes of the binary and ternary complex, respectively, and η_{ET} is the energy transfer efficiency from N-*PA* to *phen*. From the data it is obvious that the intramolecular energy transfer efficiency from N-*PA* to *phen* is rather large.

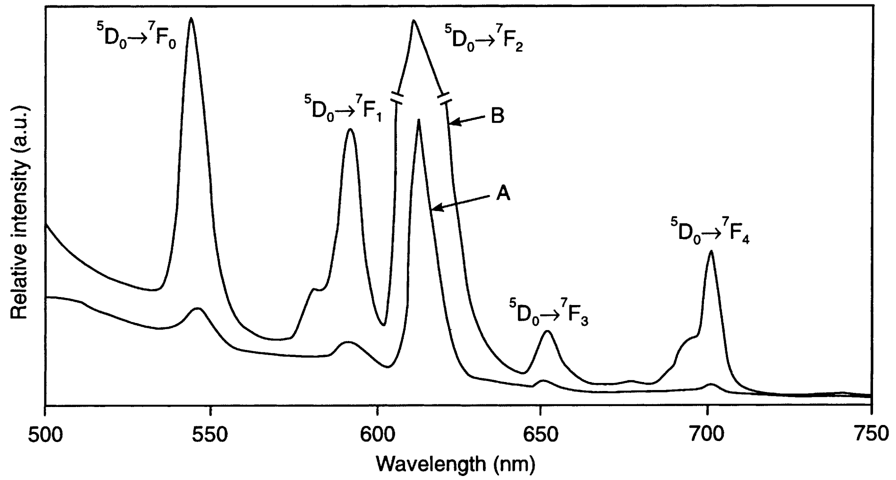

Fig. 5. Luminescence spectra of $Eu(N\text{-}PA)_3\cdot 4H_2O$ (A) and $Eu(N\text{-}PA)_3\cdot phen\cdot 2H_2O$ (B)

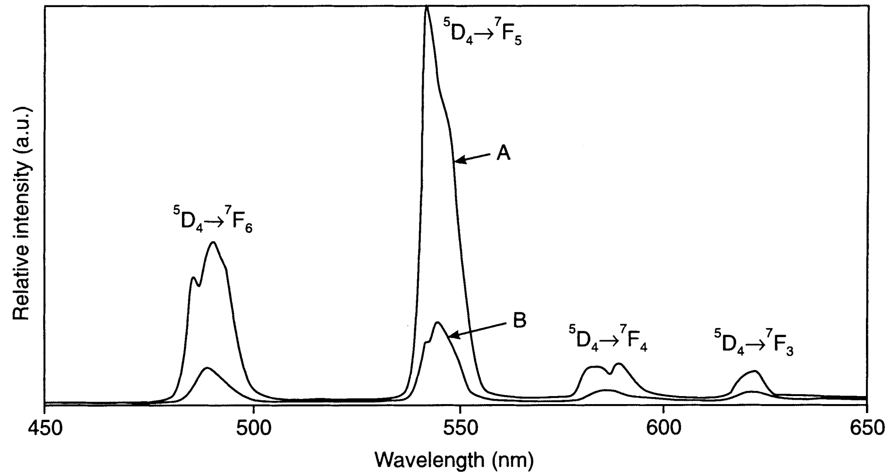

Fig. 6. Luminescence spectra of $Tb(N\text{-}PA)_3\cdot 4H_2O$ (A) and $Tb(N\text{-}PA)_3\cdot phen\cdot 2H_2O$ (B)

Therefore, in the ternary complexes the energy match between *phen* and Ln^{3+} has to be considered as the most important factor determining the luminescence properties of the complexes.

In order to confirm the prediction resulting from the energy difference between the triplet state of the ligands and the excited energy level of the rare earth ions, fluorescence spectra of binary and ternary complexes of Eu^{3+} and Tb^{3+} were measured. The luminescence spectra of all rare earth complexes are similar owing to the characteristic emission of the rare earth center ions. Different organic ligands only change the emission intensity; the emission position hardly varies. Figs. 5 and 6 show the fluorescence spectra of $Eu(N\text{-}PA)_3\cdot 4H_2O$, $Eu(N\text{-}PA)_3\cdot phen\cdot 2H_2O$, $Tb(N\text{-}PA)_3\cdot 4H_2O$, and $Tb(N\text{-}PA)_3\cdot phen\cdot 2H_2O$. In Fig. 5, the emissions of Eu(N-

Table 4. Luminescence properties of Eu^{3+} and Tb^{3+} complexes

	λ_{ex} (nm)	λ_{em} (nm)	Luminescence lifetimes (μs)	Relative intensities (a.u.)
Eu(N-*PA*)$_3$·4H_2O	322	613	361	0.7[1]
Tb(N-*PA*)$_3$·4H_2O	370	543	587	54.6[1]
Eu(N-*PA*)$_3$·*phen*·2H_2O	327	614	404	7.4[2]
Tb(N-*PA*)$_3$·*phen*·2H_2O	397	544	116	11.0[2]

[1] Excitation and emission slit width: 3 nm; [2] excitation and emission slit width: 0.5 nm

PA)$_3$·4H_2O at 545.5, 583 (595), 614, 652, and 702 nm originate from $^5D_0 \rightarrow {}^7F_0, {}^5D_0 \rightarrow {}^7F_1, {}^5D_0 \rightarrow {}^7F_2, {}^5D_0 \rightarrow {}^7F_3$, and $^5D_0 \rightarrow {}^7F_4$ transitions; the corresponding values for Eu(N-*PA*)$_3$·*phen*·2H_2O are 546, 591, 613.5, 684 (655), and 702 nm. Among these transitions, $^5D_0 \rightarrow {}^7F_2$ is the strongest. In Fig. 6, the analogous situation for the couple Tb(N-*PA*)$_3$·4H_2O (486 (491), 542.6, 583 (589), and 621.3 nm; $^5D_4 \rightarrow {}^7F_6, {}^5D_4 \rightarrow {}^7F_5, {}^5D_4 \rightarrow {}^7F_4$, and $^5D_4 \rightarrow {}^7F_3$) and Tb(N-*PA*)$_3$·*phen*·2$H_2O$ (489, 545.4, 583, and 622 nm) is shown, $^5D_4 \rightarrow {}^7F_5$ transition being the strongest among these transitions. Table 4 gives the relative luminescence intensities of Eu^{3+} complexes for $^5D_0 \rightarrow {}^7F_2$ and of Tb^{3+} complexes for $^5D_4 \rightarrow {}^7F_5$. The data indicate that the emission intensities of Tb^{3+} complexes are stronger than those of the Eu^{3+} ones. This results from the more convenient energy difference between the triplet state energy of ligands and central ions. The results also show that the luminescence intensities of ternary complexes are higher than those of binary complexes in the case of Eu^{3+}, whereas the opposite holds for Tb^{3+} complexes. This can be well explained on the basis of relative energies: if intramolecular energy transfer takes place from N-*PA* to *phen*, the difference in energy leads to a mismatch between the lowest triplet state of *phen* and the first excited state of europium. Table 4 also gives the luminescence lifetimes of the above complexes, and from these data, it can be concluded that the lifetime of Eu(N-*PA*)$_3$·*phen*·2H_2O is longer than that of Eu(N-*PA*)$_3$·4H_2O, whereas the lifetime of Tb(N-*PA*)$_3$·*phen*·2H_2O is less than that of Tb(N-*PA*)$_3$·4H_2O. This can be interpreted in a way that *phen* is used as an additional ligand to modify the luminescence properties of corresponding complexes. Binary and ternary terbium complexes with N-phenyl-2-aminobenzoic acid and 1,10-phenanthroline have excellent luminescence properties and, their further study could lead to the development of a luminescent material of great potential.

Experimental

Preparation of rare earth complexes

The rare earth oxides (Gd_2O_3, Eu_2O_3, Tb_4O_7) (99.99%) were converted to their chlorides by treatment with concentrated hydrochloric acid. The rare earth complexes with N-phenylanthranilic acid were prepared by homogeneous precipitation. An aqueous solution of rare earth chloride was added to an aqueous alcoholic solution of N-phenyl-2-aminobenzoic acid whose *pH* value was adjusted to 6.0–7.0 by addition of aqueous sodium hydrate with stirring (molar ratio of

LnCl$_3$·6H$_2$O:N-phenyl-2-aminobenzoic acid: 1:3). The precipitate was filtered off, washed with water and ethanol, dried, and stored over silica gel.

The ternary complexes were prepared in the following way: The ethanolic solution of 1,10-phenanthroline was added to the solutions of the binary complexes synthesized as above (molar ratio of binary rare earth complex to 1,10-phenanthroline: 1:1) and refluxed several hours at 343 K in a water bath. The precipitates were filtered off, washed with water and ethanol, dried, and stored over silica gel.

Measurement of the properties of rare earth complexes

Elemental analyses were carried out with a Carlo-Erba 1106 elemental analyzer. The rare earth ion contents were determined by titration with *EDTA* using xylenol orange as indicator and hexamethylene tetramine as buffer. Infrared spectra in the region of 4000–400 cm^{-1} were recorded on a Biorad infrared spectrophotometer (Model FTS-7) employing the KBr pellet technique. The TG and DTA curves were recorded on an Thermoflex DTA derivatograph at a heating rate of 10 K·min^{-1} in air (sensitivities: TG: 10 mg, DTA: $\pm 50\,\mu$V). UV/Vis spectra were measured with a UV-300 spectrophotometer. Phosphorescence spectra and phosphorescence lifetimes of gadolinium complexes were determined with a SPEX 1934D spectrophotometer at liquid nitrogen temperature in a mixed solution ($5\cdot 10^{-4}$ mol/l) of absolute ethanol and *DMF* (4:1) using a 450 W pulse xenon lamp as excitation source. Fluorescence lifetimes were obtained with the same spectrophotometer at room temperature. Fluorescence spectra were recorded on a SPEX FL-2T2 spectrofluorometer.

Acknowledgments

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References

[1] Richardson FS (1982) J Chem Rev **82**: 541
[2] De Sa FD, Nunes LHA (1993) J Alloy Compd **196**: 17
[3] Sato S, Wada M (1970) Bull Chem Soc Jpn **43**: 1955
[4] Crosby GA (1961) J Chem Phys **34**: 743
[5] Wu SL, Wu YL, Yang YS (1992) J Alloys Compd **180**: 399
[6] Yang YS, Gong ML, Li YY, Lei HY, Wu SL (1994) J Alloys Compd **207/208**: 112
[7] Basak D (1994) Asian J Chem **6**: 440
[8] Deacon GB, Phillips GJJ (1980) Coord Chem Rev **33**: 227
[9] Dexter DL (1953) J Chem Phys **21**: 836
[10] Dean CRS, Shepherd TM (1975) J Chem Soc Faraday Trans **71**: 146
[11] Zeng HY, Yang YS, Huang SH (1995) Chin J Lumin **16(4)**: 549
[12] Deschryer F, Boens N (1977) Adv Photochem **10**: 359
[13] Yan B, Zhang HJ, Wang SB, Ni JZ (1997) J Photochem Photobiol A Chem **109**: 223
[14] Yan B, Zhang HJ, Wang SB, Ni JZ (1998) Monatsh Chem **129**: 151

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