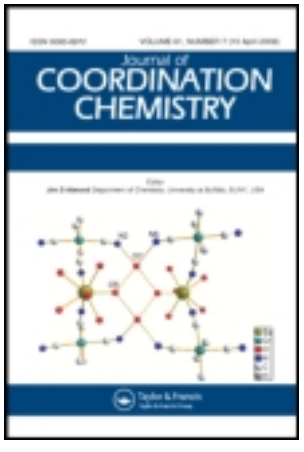

Journal of Coordination Chemistry
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gcoo20

DNA-binding properties and antioxidant activity of lanthanide complexes with the Schiff base derived from 3-carbaldehyde chromone and isonicotinyl hydrazine

Yong Li [a] & Zhengyin Yang [a]

[a] College of Chemistry and Chemical Engineering, State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou 730000, P.R. China

Version of record first published: 25 Jun 2010.

To cite this article: Yong Li & Zhengyin Yang (2010): DNA-binding properties and antioxidant activity of lanthanide complexes with the Schiff base derived from 3-carbaldehyde chromone and isonicotinyl hydrazine, Journal of Coordination Chemistry, 63:11, 1960-1968

To link to this article: http://dx.doi.org/10.1080/00958972.2010.496127

Journal of Coordination Chemistry
Vol. 63, No. 11, 10 June 2010, 1960–1968

Taylor & Francis
Taylor & Francis Group

DNA-binding properties and antioxidant activity of lanthanide complexes with the Schiff base derived from 3-carbaldehyde chromone and isonicotinyl hydrazine

YONG LI and ZHENGYIN YANG*

College of Chemistry and Chemical Engineering, State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou 730000, P.R. China

(*Received 1 August 2009; in final form 10 April 2010*)

Structural analyses indicate that the ligand and lanthanide ions form mononuclear 10-coordinate ($[Ln\ L_2 \cdot (NO_3)_2] \cdot NO_3$ [Ln(III) = La, Sm, Nd, and Yb; L is chromone-3-carbaldehyde-(isonicotinoyl) hydrazone) complexes with 1 : 2 metal-to-ligand stoichiometry. DNA-binding studies show that the ligand and its lanthanide complexes can bind to calf thymus DNA *via* an intercalation mode with binding constants of 10^5 $(\text{mol } L^{-1})^{-1}$, and the lanthanide complexes bind stronger than the free ligand alone. Antioxidant activities of the ligand and lanthanide complexes were determined by superoxide and hydroxyl radical scavenging methods *in vitro*. The ligand and complexes possess strong scavenging effects, and the lanthanide complexes show stronger antioxidant activities than the ligand and some standard antioxidants, such as vitamin C.

Keywords: Chromone-3-carbaldehyde-(isonicotinoyl) hydrazone; Lanthanide complexes; DNA-binding properties; Antioxidant activity

1. Introduction

A large percentage of chemotherapeutic anticancer drugs are compounds which interact with DNA directly or prevent the proper relaxation of DNA (through the inhibition of topoisomerases). DNA-targeting cancer drugs continue to be developed, as evidenced by the recent approval of belotecan [1, 2]. Given the applications of DNA-targeting drugs for cancer and beyond, the investigation of drug–DNA interactions is of considerable interest. Drug–DNA interactions can be classified into three major categories: intercalation, groove binding, and external static electronic effects [3]. Because DNA intercalators have been extensively used as antitumor, antineoplastic, antimalarial, antibiotic, and antifungal agents, DNA intercalation binding mode is widely studied [2]. Chromones (1-benzopyran-4-one), a group of naturally and widely distributed compounds ubiquitous in nature, especially in the plant kingdom [4], receive considerable attention, mainly due to their biological and physiological activities, such as antimycobacterial, antifungal, anticonvulsant, antimicrobial, mushroom tyrosinase

*Corresponding author. Email: yangzy@lzu.edu.cn

Journal of Coordination Chemistry
ISSN 0095-8972 print/ISSN 1029-0389 online © 2010 Taylor & Francis
DOI: 10.1080/00958972.2010.496127

inhibition activities, and intermediates to many products of fine chemical industries [5, 6]. Some hydrazones and their metal complexes often possess diverse biological and pharmaceutical activities, such as antimicrobial, antituberculostatic, anticancer, antioxidant properties [7–10]. Furthermore, Schiff bases are also able to inhibit the growth of several animal tumors, and some chelates have shown good antitumor activities against tumors [11]. Over production of activated oxygen species, superoxide anion ($O_2^{\bullet -}$) and hydroxyl radical ($HO^{\bullet}$), generated by normal metabolic process, is considered to be the main contributor to the oxidative damage of biomolecules, such as DNA, lipids, and proteins; thus, accelerating cancer, aging, inflammation, cardiovascular, and neurodegenerative diseases [12]. The potential value of antioxidants has already prompted investigators to search for the cooperative effects of metal complexes and natural compounds to improve the antioxidant activity and cytotoxicity [13].

Herein, we report the synthesis and characterization of a Schiff-base ligand, chromone-3-carbaldehyde-(isonicotinoyl) hydrazone (L), and its lanthanide complexes. Their DNA-binding modes and antioxidant activities were investigated systematically. Our work will be useful to seek and design new antitumor drugs and antioxidants, as well as to better understand the DNA-binding modes and helical conformation of nucleic acids.

2. Experimental

2.1. *Materials and instrumentation*

Ethidium bromide (EB) and calf thymus DNA (CT DNA) were purchased from Sigma Chemical Co. All chemicals and solvents were of analytical reagent grade, and used without purification unless otherwise noted.

All the experiments involved with the interaction of the ligand and complexes with CT DNA were carried out in doubly distilled water buffer containing 5 mmol L^{-1} Tris [Tris(hydroxymethyl)-aminomethane] and 50 mmol L^{-1} NaCl and adjusted to pH 7.1 with hydrochloric acid. Solution of CT DNA in Tris-HCl gave ratios of UV absorbance of about 1.8–1.9 : 1 at 260 and 280 nm, indicating that the CT DNA was sufficiently free of proteins [14]. The CT DNA concentration per nucleotide was determined spectrophotometrically by employing an extinction coefficient of 6600 $(mol\,L^{-1})^{-1}\,cm^{-1}$ at 260 nm [15]. The ligand and complexes were dissolved in a solvent mixture of 1% DMF and 99% Tris-HCl buffer (pH 7.1) at 1.0×10^{-5} mol L^{-1}.

Carbon, hydrogen, and nitrogen were determined using an Elemental Vario EL analyzer. The metal contents of the complexes were determined by titration with EDTA (xylenol orange tetrasodium salt used as indicator and hexamethylidynetetraimine as buffer). The melting points were determined on a Beijing XT4-100X microscopic melting point apparatus (the thermometer was not corrected). The IR spectra were obtained in KBr discs on a Thermo Mattson FTIR spectrophotometer from 4000 to 400 cm^{-1}. ^1H NMR spectra were recorded on a Varian VR 300 MHz spectrometer in DMSO-d_6 with tetramethylsilane (TMS) as an internal standard. Mass spectra were performed on an APEX II FT-ICR MS instrument using DMF as mobile phase. Conductivity measurements were performed in DMF solution with a DDS-11C conductometer at 25.0°C. UV-Vis spectra were recorded on a Shimadzu

UV-240 spectrophotometer. Fluorescence spectra were recorded on a Hitachi RF-4500 spectrofluorophotometer at constant room temperature.

2.2. *Preparation of the ligand (L)*

Scheme of the synthesis of the ligand is shown in figure 1. 3-Carbaldehyde chromone was prepared according to the literature methods [16]. An ethanol solution containing isonicotinyl hydrazine (1.37 g, 10 mmol) was added dropwise to another ethanol solution containing 3-carbaldehyde chromone (1.74 g, 10 mmol). The mixture was refluxed on an oil bath for 2 h with stirring and a yellow precipitate was formed. The yellow precipitate was filtered, washed several times with ethanol, and recrystallized from DMF and water to give L, which was then dried in a vacuum. Yield: 73.3%; m.p. 187–189°C; Anal. Calcd for $C_{16}H_{11}N_3O_3$: C, 65.5; H, 3.8; N, 14.3; Found (%): C, 65.8; H, 3.7; N, 14.4. IR ν_{max} (cm^{-1}): $\nu_{(carbonyl)C=O}$: 1648, $\nu_{(hydrazonic)C=O}$: 1702, $\nu_{C=N}$: 1601 cm^{-1}. U_{max} (nm): 266, 302 nm. L (DMSO-d_6 300 MHz): δ 11.83 (1H, s, =NNH), 8.85 (1H, s, 9-H), 8.78 (2H, d, $J = 6.3$ Hz, 11, 11′-H), 8.64 (1H, s, 2-H), 8.13 (1H, d, $J = 8.7$ Hz, 5-H), 7.88 (3H, m, PhH, 7, 10, 10′-H), 7.72 (1H, d, $J = 1.7$ Hz, 8-H), 7.55 (1H, t, $J = 8.7$, 2.5 Hz, 6-H).

2.3. *Preparation of the complexes*

The ligand (1.0 mmol, 0.293 g) and La(III) nitrate (0.5 mmol, 0.217 g) were added together in ethanol (150 mL). The solution was refluxed on an oil bath for 2 h with stirring and a white precipitate, the La(III) complex, was separated from the solution by suction filtration, purified by washing several times with ethanol, and dried for 24 h in a vacuum. Sm(III), Nd(III), and Yb(III) complexes were prepared in the same way. Anal. Calcd for La(III) complex $C_{32}H_{22}N_9O_{15}La$: C, 42.2; H, 2.4; N, 13.8; La, 15.2; Found (%): C, 42.3; H, 2.5; N, 13.5; La, 15.2. IR ν_{max} (cm^{-1}): $\nu_{(carbonyl)C=O}$: 1589, $\nu_{(hydrazonic)C=O}$: 1635, $\nu_{C=N}$: 1560, ν_{NO_3}: 1469, 1388, 1322, 1180, 821, ν_{M-O}: 603, ν_{M-N}: 434 cm^{-1}. U_{max} (nm): 275, 307 nm. Λ_m ($S\,cm^2\,mol^{-1}$): 80.5. Anal. Calcd for

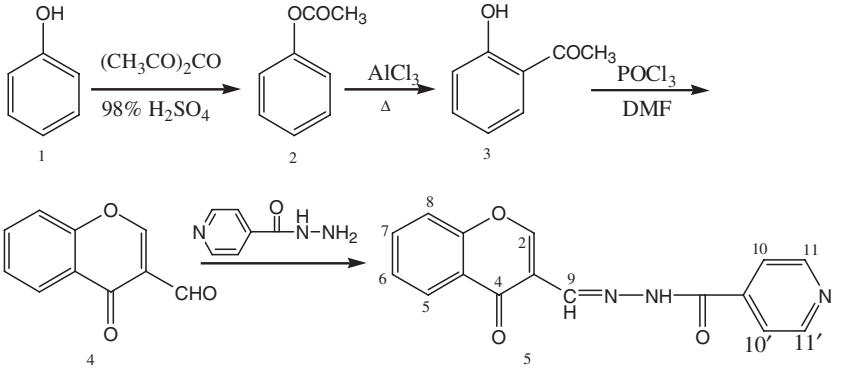

Figure 1. Synthesis of the ligand (L).

Sm(III) complex $C_{32}H_{22}N_9O_{15}Sm$: C, 41.6; H, 2.4; N, 13.7; Sm, 16.3. Found (%): C, 41.5; H, 2.5; N, 13.6; Sm, 16.3. IR ν_{max} (cm^{-1}): $\nu_{(carbonyl)C=O}$: 1616, $\nu_{(hydrazonic)C=O}$: 1638, $\nu_{C=N}$: 1576, ν_{NO_3}: 1483, 1394, 1324, 1182, 817, ν_{M-O}: 608, ν_{M-N}: 420 cm^{-1}. U_{max} (nm): 273, 307 nm. Λ_m ($S\,cm^2\,mol^{-1}$): 88.5. Anal. Calcd for Nd(III) complex $C_{32}H_{22}N_9O_{15}Nd$: C, 41.9; H, 2.4; N, 13.8; Nd, 15.7. Found (%): C, 41.8; H, 2.4; N, 13.7; Nd, 15.6. IR ν_{max} (cm^{-1}): $\nu_{(carbonyl)C=O}$: 1627, $\nu_{(hydrazonic)C=O}$: 1639, $\nu_{C=N}$: 1562, ν_{NO_3}: 1462, 1390, 1320, 1180, 813, ν_{M-O}: 604, ν_{M-N}: 427 cm^{-1}. U_{max} (nm): 275, 308 nm. Λ_m ($S\,cm^2\,mol^{-1}$): 75.7. Anal. Calcd for Yb(III) complex $C_{32}H_{22}N_9O_{15}Yb$: C, 40.6; H, 2.3; N, 13.3;Yb, 18.3. Found (%): C, 40.7; H, 2.4; N, 13.3; Yb, 18.4. IR ν_{max} (cm^{-1}): $\nu_{(carbonyl)C=O}$: 1614, $\nu_{(hydrazonic)C=O}$: 1636, $\nu_{C=N}$: 1578, ν_{NO3}: 1466, 1384, 1322, 1181, 815, ν_{M-O}: 601, ν_{M-N}: 416 cm^{-1}. U_{max} (nm): 276, 306 nm. Λ_m ($S\,cm^2\,mol^{-1}$): 91.0.

3. Results and discussion

3.1. *Structure of Ln(III) complexes*

The lanthanide complexes were prepared by direct reactions of chromone-3-carbaldehyde-(isonicotinoyl) hydrazone (L) with appropriate mole ratios of $Ln(NO_3)_3 \cdot 6H_2O$ (Ln = La, Sm, Nd, and Yb) in ethanol. All the lanthanide complexes are yellow powders, stable in atmospheric conditions for extended periods, and easily soluble in DMF and DMSO; slightly soluble in ethanol, methanol, and acetone; insoluble in benzene, water, and diethyl ether. The melting points of the lanthanide complexes exceed 300°C. The molar conductivities of lanthanide complexes are around 75.7–91.0 $S\,cm^2\,mol^{-1}$ in DMF solution indicating that all of them are 1 : 1 electrolytes [17]. Elemental analyses indicate that all the lanthanide complexes are 1 : 2 metal-to-ligand stoichiometry.

IR spectra of the lanthanide complexes are similar. $\nu_{(carbonyl)C=O}$ and $\nu_{(hydrazonic)C=O}$ of the free ligand appear at 1648 and 1702 cm^{-1}, respectively, and for the complexes these shift to 1616 and 1638 cm^{-1} with $\Delta\nu_{(ligand-complexes)}$ equal to 30 and 64 cm^{-1}. A band at 608 cm^{-1} is assigned to ν_{M-O}, demonstrating that the oxygen of carbonyl has formed a bond with lanthanide [18]. The shifts of the wavenumbers indicate that the Ln–O (hydrazonic) bond is stronger than the Ln–O (carbonyl) bond. The band at 1601 cm^{-1} for free ligand assigned to $\nu_{C=N}$ shifts to 1576 cm^{-1} for the complexes, $\Delta\nu_{(ligand-complexes)}$ of 25 cm^{-1}. Weak bands at 420 cm^{-1} are assigned to ν_{M-N} in the complexes, confirming that nitrogen of the imino-group bonds to lanthanide ions [19]. Absorption bands of the coordinated nitrates were observed at 1483 (ν_{as}) and 817 (ν_s) cm^{-1}. The ν_3 (E′) of free nitrates appear at 1394 cm^{-1} for the complexes. In addition, the separation of the two highest frequency bands $|\nu_4 - \nu_1|$ is approximately 160 cm^{-1}, and accordingly the coordinated NO_3^- is bidentate [20].

UV-Vis spectra of the ligand and lanthanide complexes were measured in Tris-HCl buffer solution. Electronic spectra of the ligand have a strong band at $U_{max} = 266$ nm ($\varepsilon = 1.70 \times 10^4\,(mol\,L^{-1})^{-1}\,cm^{-1}$) and a medium band at $U_{max} = 302$ nm ($\varepsilon = 9.36 \times 10^3\,(mol\,L^{-1})^{-1}\,cm^{-1}$). Lanthanide complexes also yield two bands, shifted to 273–276 nm ($\varepsilon = 1.04 - 2.41 \times 10^4\,(mol\,L^{-1})^{-1}\,cm^{-1}$) and 306–308 nm ($\varepsilon = 2.51 - 2.76 \times 104\,(mol\,L^{-1})^{-1}\,cm^{-1}$).

The electrospray ionization (ESI) mass spectra of La(III) complex show peaks at 786, 723, and 294, which can be assigned to the fragments [La(III) complex$-2NO_3$–H]$^+$, [La(III) complex–$3NO_3$–2H]$^+$, and [La(III) complex–$3NO_3$–L–La + H]$^+$, respectively.

Since the crystal structures of the Ln(III) complexes have not been obtained, we determined the structures of Ln(III) complexes on the basis of elemental analyses, molar conductivities, mass spectra, IR spectra, UV-Vis spectra, and our previous work [21–23], indicating that the ligand and lanthanide ions form mononuclear 10-coordinate [Ln $L_2 \cdot (NO_3)_2] \cdot NO_3$ [Ln(III) = La, Sm, Nd, and Yb; L is chromone-3-carbaldehyde-(isonicotinoyl) hydrazone] complexes with 1 : 2 metal-to-ligand stoichiometry at the Ln(III) centers (figure 2).

3.2. *DNA-binding properties*

Methods of investigating DNA-binding properties, such as electronic absorption titration, fluorescence spectra, and viscosity measurements are given in the Supplementary material. Electronic absorption titration is one of the most useful techniques for DNA-binding studies of metal complexes. The absorption spectra of the ligand and complexes in the absence and presence of DNA are similar and absorption spectra of Nd(III) complex are given (figure S1). In the presence of DNA, absorption bands at 275 nm for the ligand, La(III), Sm(III), Nd(III), and Yb(III) complexes exhibited hypochromism of about 14.68%, 31.34%, 24.36%, 41.78%, and 24.57%, respectively. Absorption bands at 308 nm for the ligand, La(III), Sm(III), Nd(III), and Yb(III) complexes also exhibited hypochromism of about 32.46%, 41.04%, 37.80%, 41.31%, and 37.30%, respectively, accompanied by a small red shift of no more than 3 nm. Moreover, isobetic points at 335–342 nm for the ligand and complexes are observed, indicating an equilibrium between the investigated compound and DNA. These results suggest an intimate association of the compound with DNA *via* intercalation. After intercalating the base pairs of DNA into the compound, the π^* orbital of the intercalated ligand can couple with the π orbital of the DNA base pairs,

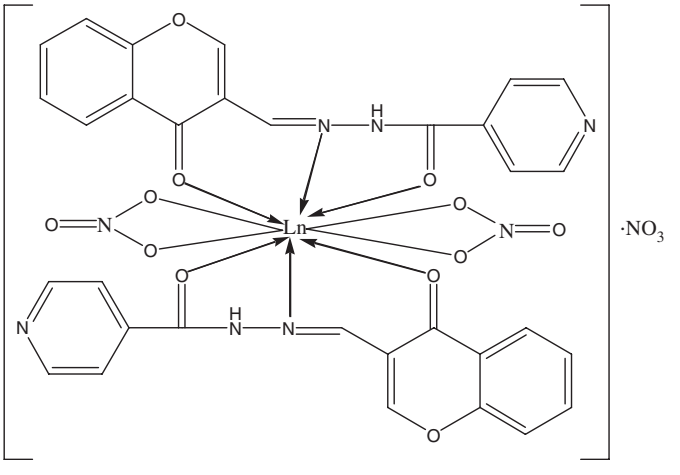

Figure 2. Suggested structure of the Ln(III) complexes.

thus, decreasing the $\pi \rightarrow \pi^*$ transition energy and resulting in the bathochromism. The coupling π orbital is partially filled by electrons, thus, decreasing the transition probabilities and concomitantly resulting in hypochromism [24]. Nd(III) complex shows more hypochromicity than the free ligand and other complexes, indicating that the binding strength of Nd(III) complex is stronger than the other compounds.

In order to test if the compounds bind to DNA *via* intercalation, EB was employed (figure S2) because EB interacts with DNA as a typical indicator of intercalation. The maximal absorption of EB at 479 nm decreases and shifts to 486 nm in the presence of CT DNA, which is a characteristic of intercalation. Curve (b) shows the absorption of a mixed solution of EB, DNA, and Nd(III) complex. The absorption at 494 nm increases compared with curve (c). These may result from two reasons: (1) EB bound to the free ligand and complexes strongly, resulting in decrease of the amount of EB intercalated into DNA; (2) there exists competitive intercalation between the compounds and EB with DNA, so releasing some free EB from the DNA–EB system. However, the former reason could be precluded because there were no new absorption peaks appearing.

Upon addition of DNA, the fluorescence emission intensity of every investigated compound increases steadily at room temperature (figure S3). According to the Scatchard equation, a plot of r/C_f *versus* r gave the intrinsic binding constants K_b of $(2.2 \pm 0.3) \times 10^5$, $(4.0 \pm 0.6) \times 10^5$, $(2.6 \pm 0.5) \times 10^5$, $(7.6 \pm 0.9) \times 10^5$, $(3.1 \pm 0.5) \times 10^5$ $(\text{mol L}^{-1})^{-1}$ from the fluorescence data for the ligand, La(III), Sm(III), Nd(III), and Yb(III) complexes, respectively. The Stern–Volmer plot is linear, indicating that only one type of binding process occurs. Fluorescence increasing may be attributed to the compounds protected from solvent water by the hydrophobic environment inside the DNA helix [25]. Results obtained from fluorescence titrations show that the lanthanide complexes bind to DNA more strongly than the free ligand, probably attributed to the extension of the π system of the intercalated ligand and the coordination of lanthanide ions, which can lead to a planar area greater than that of the free ligand and the coordinated ligand penetrating more deeply into and stacking more strongly with the DNA base pairs.

The emission spectra of EB bound to DNA in the absence and the presence of every compound have been recorded for $[\text{EB}] = 4 \times 10^{-7}\,\text{M}$, $[\text{DNA}] = 5 \times 10^{-6}\,\text{M}$ for increasing amounts for every compound; emission fluorescence intensities of the DNA–EB system decrease with the increasing amounts of Nd(III) complex (figure S4). The emission band at 589 nm of the DNA–EB system decreases in fluorescence intensity upon addition of every compound at diverse r (=[Compound]/[DNA]) values indicating competition of the compounds with EB in binding to DNA. The observed quenching of DNA–EB fluorescence intensity for the compounds suggests that they displace EB from the DNA–EB system and interact with DNA *via* the intercalative mode [26]. The quenching constants K_q are often used to evaluate the quenching efficiency for every compound and vary with experimental conditions. K_q values are given by the ratio of the slope to the intercept and K_q values for the ligand and La(III), Sm(III), Nd(III), and Yb(III) complexes are $(2.57 \pm 0.03) \times 10^4\,(\text{mol L}^{-1})^{-1}$, $(3.2 \pm 0.2) \times 10^4\,(\text{mol L}^{-1})^{-1}$, $(2.7 \pm 0.2) \times 10^4\,(\text{mol L}^{-1})^{-1}$, $(5.7 \pm 0.4) \times 10^4\,(\text{mol L}^{-1})^{-1}$, and $(3.1 \pm 0.3) \times 10^4$ $(\text{mol L}^{-1})^{-1}$, respectively. Experimental results indicate that all compounds bind to DNA *via* intercalation and the complexes bind to DNA more strongly than the free ligand [27].

A useful technique to prove intercalation is viscosity measurements, which are sensitive to length changes of DNA and regarded as the least ambiguous and the most critical tests of binding mode in the solution in the absence of crystallographic structural data or NMR spectra [28]. Under appropriate conditions, the intercalation of drugs, such as EB causes a significant increase in the viscosity of DNA solution due to the increase in separation of base pairs of intercalation sites and hence results in an increase in overall DNA contour length. On the other hand, drugs such as $[Ru(bpy)_3]^{2+}$, which interacts with DNA by an electrostatic binding mode, have no influence on DNA viscosity [29]. Upon increasing the amounts of our compounds, the relative viscosities of DNA increase steadily with the increasing concentrations of compounds (figure S5). The increased degree of viscosity, which depend on the binding affinity of compounds to DNA, follow the order Nd(III) complex > La(III) complex > Yb(III) complex > Sm(III) complex > L. Experimental results suggest that all the complexes and ligand intercalate between DNA base pairs and the binding affinities of the complexes are higher than that of the free ligand.

On the basis of all the spectroscopic studies together with the viscosity measurements, we find that the free ligand and its lanthanide complexes bind to DNA *via* an intercalative mode and the complexes bind to DNA more strongly and deeply than the free ligand (figure 3).

3.3. *Antioxidant activity*

Methods of investigating antioxidant activity of the ligand and its complexes are given in the Supplementary material. IC_{50} values for the ligand and complexes for $HO^{\bullet}$ are 28.55 and 3.62–10.48 μmol L^{-1}, respectively (figure S6a). The inhibitory effect of the compounds is marked and the average suppression ratio for $HO^{\bullet}$ increases with increasing compound concentration. The average suppression ratio of the lanthanide complexes is higher than the free ligand due to the chelation of organic molecules to La(III), Sm(III), Nd(III), Yb(III), which can exert selective effects on scavenging radicals of the biological system. The plots of superoxide radical scavenging effect (%) for the ligand and complexes have been made (figure S6b). Inhibitory effect of the compounds tested on $O_2^{\bullet-}$ is concentration dependent and the suppression ratio increases with the increasing sample concentrations in the range tested. The average suppression ratio of the free ligand ($IC_{50} = 96.02$ μmol L^{-1}) for $O_2^{\bullet-}$ is the least and La(III) complex ($IC_{50} = 2.34$ μmol L^{-1}) is the most effective. The IC_{50} value of ascorbic

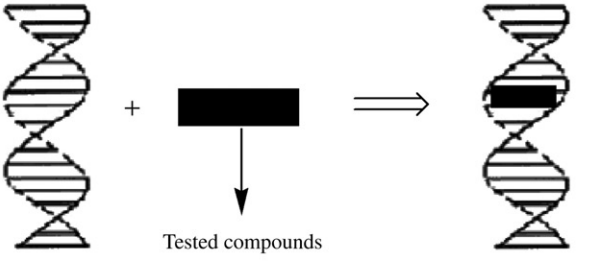

Figure 3. Molecular mode for Ln(III) complexes (*via* an intercalation mode).

acid (Vc, a standard agent for non-enzymatic reaction) for $HO^{\bullet}$ is 1.537 mg ml^{-1} (8.727 mmol), and the scavenging effect for $O_2^{\bullet-}$ is only 25% at 1.75 mg ml^{-1} (9.94 mmol) [30]. Notably, the investigated ligand and lanthanide complexes have much stronger scavenging abilities for $HO^{\bullet}$ and $O_2^{\bullet-}$ radicals than the standard antioxidant (vitamin C).

4. Conclusion

A novel ligand, chromone-3-carbaldehyde-(isonicotinoyl) hydrazone, and its La(III), Sm(III), Nd(III), and Yb(III) complexes were synthesized. The structures of the Ln(III) complexes were determined on the basis of elemental analyses, molar conductivities, IR spectra, ^{1}H NMR spectra, mass spectra, and UV-Vis spectra. With the changes of UV-Vis spectra, fluorescence spectra, and relative viscosities of DNA, DNA-binding studies indicate that the ligand and lanthanide complexes bind to DNA *via* an intercalation mode and the lanthanide complexes bind to DNA more strongly and deeply than the free ligand. This is due to the lanthanide complexes having two parallel M–L planes, which may well be an indicator of the intercalation behavior of these complexes binding to DNA. The lanthanide complexes possess better antioxidant activity than the ligand because of the chelating effects between the ligand and lanthanide ions. Results obtained from this work would be useful to understand the mechanism of interactions of small molecules binding to DNA and helpful in the development of potential applications in the biological, pharmaceutical, and physiological fields in the future.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (20475046) and Gansu NSF (0710RJZA012).

References

[1] M. Hegde, A.D. Schmidt. *Annu. Rep. Med. Chem.*, **40**, 443 (2005).
[2] R. Palchaudhuri, P.J. Hergenrother. *Curr. Opin. Biotechnol.*, **18**, 1 (2007).
[3] S. Mahadevan, M. Palaniandavar. *Inorg. Chim. Acta*, **254**, 291 (1997).
[4] V.Y. Sosnovskikh. *Russ. Chem. Rev.*, **72**, 489 (2003).
[5] G. Singh, R. Singh, N.K. Girdhar, M.P.S. Ishar. *Tetrahedron*, **58**, 2471 (2002).
[6] L.Z. Piao, H.R. Park, Y.K. Park, S.K. Lee, J.H. Park, M.K. Park. *Chem. Pharm. Bull.*, **50**, 309 (2002).
[7] B.K. Kaymakcioglu, S. Rollas. *Farmaco*, **57**, 595 (2002).
[8] S. Küçükgüzel, S. Rollas, I. Küçükgüzel, M. Kiraz. *Eur. J. Med. Chem.*, **34**, 1093 (1999).
[9] S.R. Zhang, A.D. Sherry. *J. Solid State Chem.*, **171**, 38 (2003).
[10] Z.Y. Yang. *Synth. React. Inorg. Met. Org. Chem.*, **30**, 1265 (2000).
[11] E.M. Nddnett, P.D. Mooney. *J. Med. Chem.*, **15**, 339 (1972).
[12] S.Y. Yu, S.X. Wang, Q.H. Luo, L.F. Wang, R.P. Zhou, G. Xing. *Polyhedron*, **12**, 1093 (1993).
[13] S.Y. Chiang, J. Welch, F.J. Rauscher, T.A. Beerman. *Biochemistry*, **33**, 7033 (1994).
[14] Y.Z. Cai, Q. Luo, M. Sun, H. Corke. *Life Sci.*, **74**, 2157 (2004).
[15] K.E. Heim, A.R. Tagliaferro, D.J. Bobilya. *J. Nutr. Biochem.*, **13**, 572 (2002).

[16] A. Nohara, T. Umetani, Y. Sanno. *Tetrahedron Lett*., **14**, 1995 (1973).
[17] W.J. Geary. *Coord. Chem. Rev*., **7**, 81 (1971).
[18] F. Marchetti, C. Pettinari, R. Pettinari, A. Cingolani, D. Leonesi, A. Lorenzotti. *Polyhedron*, **18**, 3041 (1999).
[19] K.K. Narang, V.P. Singh. *Transition Met. Chem*., **18**, 287 (1993).
[20] B.D. Wang, Z.Y. Yang, D.W. Zhang, Y. Wang. *Spectrochim. Acta, Part A*, **63**, 213 (2006).
[21] B.D. Wang, Z.Y. Yang, Q. Wang, T.K. Cai, P. Crewdson. *Bioorg. Med. Chem*., **14**, 1880 (2006).
[22] B.D. Wang, Z.Y. Yang, D.D. Qin, Z.N. Chen. *J. Photochem. Photobiol. A: Chem*., **194**, 49 (2008).
[23] B.D. Wang, Z.Y. Yang, T.R. Li. *Bioorg. Med. Chem*., **14**, 6012 (2006).
[24] A.M. Pyle, J.P. Rehmann, R. Meshoyrer, C.V. Kumar, N.J. Turro, J.K. Barton. *J. Am. Chem. Soc*., **111**, 3051 (1989).
[25] H. Xu, K.C. Zheng, L.J. Lin, H. Li, Y. Gao, L.N. Ji. *J. Inorg. Biochem*., **98**, 87 (2004).
[26] M. Lee, A.L. Rhodes, M.D. Wyatt, S. Forrow, J.A. Hartley. *Biochemistry*, **32**, 4237 (1993).
[27] M. Chauhan, K. Banerjee, F. Arjmand. *Inorg. Chem*., **46**, 3072 (2007).
[28] S. Satyanarayana, J.C. Dabrowiak, J.B. Chaires. *Biochemistry*, **31**, 9319 (1992).
[29] S. Satyanarayana, J.C. Dabrowiak, J.B. Chaires. *Biochemistry*, **32**, 2573 (1993).
[30] R. Xing, H. Yu, S. Liu, W. Zhang, Q. Zhang, Z. Li, P. Li. *Bioorg. Med. Chem*., **13**, 1387 (2005).