New diethoxo-bridged dinuclear Cr(III) complexes with derivatives of the quinoxaline-2,3-dione ligand and 2,2′-bipyridine as a co-ligand: Syntheses, spectral characterizations, magnetic properties, antimicrobial inhibitory activities and interpretation of the electronic absorption spectra using the ZINDO/S-CI semi-empirical method

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ABSTRACT

Two new diethoxo-bridged dinuclear Cr(III) complexes, $[Cr(QX)(bpy)EtO]_2$ [QX = 6,7-dichloroquinoxaline-2,3-dione (**1**); 6,7-dimethylquinoxaline-2,3-dione (**2**)], have been synthesized and characterized. The complexes were initially characterized on the basis of their elemental and mass analyses. The infrared studies were useful in assigning the coordination mode of the quinoxaline-2,3-dione ligand to the chromium metal. In addition, the presence of μ-ethoxo bridges was inferred from the characteristic vibrational bands in the IR spectra of both complexes. The structural and vibrational behaviors of both complexes have been elucidated using a parameterized PM3 semi-empirical method. The magnetic susceptibility, measured at 298 K, indicated exchange interactions between the two Cr(III) centers. The observed effective magnetic moments have been correlated to the calculated Cr···Cr distances and Cr–O–Cr angles of the $Cr(OEt)_2Cr$ cores in both complexes. The ESR spectra have been recorded on powder samples at 293 K. The dominant quintet state has been computer-simulated with the parameters $J = 23$ cm^{-1}, $g = 2.11$, $D = 0.074$ cm^{-1} and $E = 0.008$ cm^{-1} for **1**. On the other hand, the spectrum of complex **2**, which showed two slightly different Cr centers, has been simulated with $J = 17$ cm^{-1}, $g_1 = 2.17$, $D_1 = 0.063$ cm^{-1}, $E_1 = 0.012$ cm^{-1} for site 1 and $g_2 = 2.055$, $D_2 = 0.065$ cm^{-1} and $E_2 = 0.0087$ cm^{-1} for site 2. The electronic spectra of the studied complexes were dominated by charge-transfer, [Cr(d$_\pi$) → bpy(π^*) and QX(O-p$_\pi$) → Cr(d$_{\pi^*}$)], and spin-allowed d–d transitions. In addition, low-energy maxima characteristics of the dinuclear transition metal complexes were observed in the 550–1050 nm region. Theoretical studies of the electronic spectra by the ZINDO/S-CI method were useful in interpreting the observed electronic transitions. The antimicrobial activity studies have indicated a significant inhibitory activity of complex **2** against the studied bacteria and complex **1** showed the highest inhibitory activity against the studied fungi.

1. Introduction

Understanding the influence of intermolecular interactions on the magnetic and spectroscopic properties of multinuclear transition metal centers has been long-standing interest in inorganic chemistry, especially due to the presence of metal clusters in biological systems [1]. Metalloproteins containing multinuclear active sites exhibit unique ground state properties and excited state spectral features which are associated with the interactions between the metal centers. The excited states of binuclear transition metal systems have also been known to exhibit spectroscopic effects due

to dimer interactions [2]. Thus, intensity enhancements of the low-energy bands corresponding to ligand-field d–d transitions have been observed for dinuclear Cr(III), Mn(II) and Fe(III) complexes as a result of the dinuclear interactions [3–5].

Due to the dependence of the dinuclear interactions on both the structure and symmetry of the organic ligands coordinating to the central metals in the complexes, dinuclear μ-OR species bearing various chelating ligands offer interesting possibilities to tune the metal-to-metal exchange interactions by small structural changes of the peripheral ligands and the μ-OR moieties [6]. With respect to the μ-OR unit, the magnetic exchange interaction between the metal centers in dimeric complexes has been shown to vary with the M–O–M bridging angle and the M–O bond length [7].

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Our interest in this field has been focused on μ-oxo, μ-hydroxo and μ-methoxo dinuclear Fe, Cr and Mo complexes [8–11]. In the present work, we have developed a synthetic procedure to synthesize two new di-μ-ethoxo dinuclear Cr(III) complexes with the general chemical formulae [Cr(DCQX)(bpy)EtO]$_2$ and [Cr(DMQX)(bpy)EtO]$_2$ (DCQX = 6,7-dichloroquinoxaline-2,3-dione; DMQX = 6,7-dimethyquinoxaline-2,3-dione). To the best of our knowledge, these dimeric complexes are considered to be amongst the few di-μ-ethoxo binuclear dichromium(III) complexes that have been reported and are the first di-μ-ethoxo binuclear dichromium(III) complexes of the quinoxaline-2,3-dione ligand. Our aim is to synthesize two dimeric complexes of the quinoxaline-2,3-dione ligand and to study the effects of structural changes in the ligand on the magnetic, spectroscopic and biological behaviors of the complexes.

2. Experimental

Chromium hexacarbonyl (Cr(CO)$_6$), 2,2'-bipyridine (bpy), oxalic acid (C$_2$H$_2$O$_4$·2H$_2$O), 4,5-dichloro-1,2-phenylenediamine and 4,5-methyl-1,2-phenylenediamine were used as purchased from Sigma–Aldrich Chemical Co. Inc. The 6,7-dichloroquinoxaline-2,3-dione (DCQX) and 6,7-dimethylquinoxaline-2,3-dione (DMQX) ligands were synthesized following the reported procedure [12]. All solvents were dried according to standard procedures.

Elemental analysis was performed using a Perkin–Elmer 2400 CHN elemental analyzer. The mass spectra were obtained on a JEOL JMS-AX500 mass spectrometer. The infrared spectra (4000–400 cm^{-1}) were recorded as KBr pellets on a Unicam Mattson 1000 FTIR spectrometer. Magnetic susceptibility measurements were carried out on a Sherwood MK1 Scientific Magnetic Susceptibility Balance at 298 K. The EPR spectra were recorded on powder samples at the X-band (9.75 GHz) with an EMX Bruker spectrometer at 293 K. The electronic absorption spectra were recorded using a Unicam UV2-300 UV–Vis spectrometer. The sample concentrations of 5.08×10^{-4} and 5.14×10^{-4} mol dm^{-3} for [Cr(DCQX)(bpy)EtO]$_2$ and [Cr(DMQX)(bpy)EtO]$_2$, respectively, in DMSO were measured against the solvent in the reference cell.

The antimicrobial activity of tested samples of the ligands and the complexes were determined using a modified Kirby–Bauer disc diffusion method [13]. A 100 µL of the tested bacteria or fungi were grown in 10 mL of fresh media until they reached a count of approximately 108 cells/mL for bacteria and approximately 105 cells/mL for fungi. A 100 µL of microbial suspension was spread onto agar plates corresponding to the broth in which they were maintained. Plates inoculated with Gram-positive bacteria (*Staphylococcus aureus*) and Gram-negative bacteria (*Escherichia coli*) were incubated at 35–37 °C for 24–48 h whereas, filamentous fungus (*Aspergillus flavus*) and yeast fungus (*Candida albicans*) were incubated at 25 °C for 48 h and 30 °C for 24–48 h, respectively. Then the diameters of the inhibition zones were measured in millimeters. Standard discs of tetracycline (antibacterial agent) and Amphotericin (antifungal agent) served as positive controls for the antimicrobial activity, while filter discs impregnated with 10 µL of DMSO solvent were used as a negative control. Blank paper discs with a diameter of 8.0 mm were impregnated with 10 µL of the tested samples stock solution (0.02 g/ mL) and inhibition zone diameters were measured.

The semi-empirical calculations in this study have been carried out using the HYPERCHEM 7.5 program package [14]. The Polak–Ribiere version of the conjugate gradient method was used in all energy minimization calculations with a coverage criterion less than 1.0×10^{-3} kcal mol^{-1} Å^{-1}. First and separately the DCQX and DMQX ligands have been optimized and the results obtained have been applied in each calculation thereafter. The values of

Cr–O and Cr–N bond lengths and angles in the literatures were used as the starting inputs [15–19]. Initial optimization of the complexes was performed by molecular mechanics (MM+). The geometry was further refined using the parameterized PM3 method. Available parameters for Cr and Cl elements were implemented in the PM3 semi-empirical method [20,21], then the parameterized PM3 method was used for geometry optimization of the complexes under study. Triplet state URHF spin pairing has been selected in addition to the standard SCF (with accelerated convergence). The theoretical harmonic vibrational frequencies were related to the experimental fundamentals by the optimum scaling factor λ, determined through a least-squares procedure given by $\lambda = \sum_i^{all} \omega_i^{theor} v_i^{expt} / \sum_i^{all} (\omega_i^{theor})^2$, where ω_i^{theor} and v_i^{expt} are the ith theoretical harmonic and ith experimental fundamental frequencies (in cm^{-1}) [22]. The molecular root mean square error (rms) was calculated by the square root of the sum over all the modes of Δ_{min} given in Ref. [22], where Δ_{min} is the minimized residual for each mode. The ZINDO/S-CI method is parameterized to produce UV–Vis electronic transitions and has been used to estimate the energies and shapes of the frontier orbitals for the complexes [23,24]. The maximum excitation energy for configuration interaction calculations was 8.0 eV. The overlap weighing factors $f_{\sigma\sigma}$ and $f_{\pi\pi}$ were taken as 1.267 and 0.585, which had been used with good success for transition metals [25,26].

EasySpin, a computational package for spectral simulation and analysis in ESR based on Matlab computational software, was used to perform a simulation of the experimental ESR spectra of the two dimeric complexes [27].

2.1. Synthesis of the [Cr(DCQX)(bpy)EtO]$_2$ complex (**1**)

2,2'-Bipyridine (0.071 g, 0.455 mmol) was added to a solution containing 0.100 g (0.454 mmol) of Cr(CO)$_6$ in 50 mL of THF. The mixture was refluxed for 2 h with continuous stirring. The resulting orange colored solution was cooled down to room temperature. DCQX (0.104 g, 0.450 mmol) was dissolved in 20 mL of EtOH and slowly added to the reaction mixture. The contents were refluxed for 18 h with continuous stirring, and during this time the brown solid product separated from solution. The solid was isolated, washed with 15 mL THF/EtOH (1:1) and dried in vacuum. A concentrated solution of the product in DMSO/EtOH (3:1) was allowed to evaporate slowly for 2 weeks, which resulted in a reddish-brown powder. Washing the powdery solid with EtOH followed by diethyl ether and then drying overnight in vacuum resulted in 0.13 g (59.6% yield) of the pure product (one brown spot in a TLC test). Attempts to obtain crystals suitable for X-ray crystallography were unsuccessful due to the limited solubility of the synthesized complex in most common solvents.

Anal. Calc. for C$_{40}$H$_{34}$Cl$_4$Cr$_2$N$_8$O$_6$ (Mr = 968.55): C, 49.60; H, 3.54; Cl, 14.64; N, 11.57. Found: C, 49.53; H, 3.52; Cl, 14.70; N, 11.62%. Effective magnetic moment at 298 K, μ_{eff} (BM): 2.955.

2.2. Synthesis of the [Cr(DMQX)(bpy)EtO]$_2$ complex (**2**)

The [Cr(DMQX)(bpy)EtO]$_2$ complex was synthesized with a similar procedure to that for [Cr(DCQX)(bpy)EtO]$_2$ using DMQX (0.086 g, 0.452 mmol) instead of DCQX. A brown powder of the product was obtained (0.11 g, 54.9% yield) after recrystallization of a concentrated solution of the complex from DMSO/EtOH/benzene (4:1:0.3).

Anal. Calc. for C$_{44}$H$_{46}$Cr$_2$N$_8$O$_6$ (Mr = 886.89): C, 59.58; H, 5.23; N, 12.64. Found: C, 59.48; H, 5.25; N, 12.67%. Effective magnetic moment at 298 K, μ_{eff} (BM): 3.116.