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Article

Diradical Character of Neutral Heteroleptic Bis(1,2-dithiolene) Metal Complexes: Case Study of [Pd(Me_2timdt)(mnt)] (Me_2timdt = 1,3-Dimethyl-2,4,5-trithioxoimidazolidine; mnt^{2-} = 1,2-Dicyano-1,2-ethylenedithiolate)

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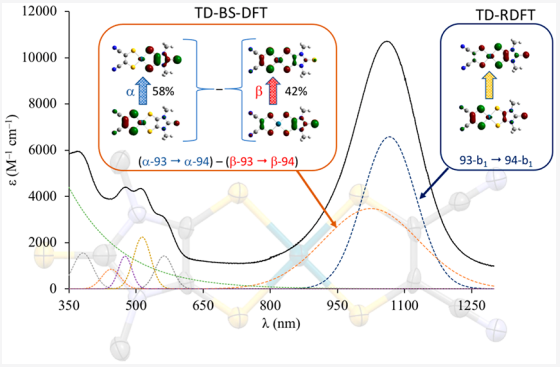
ABSTRACT: The reaction of the bis(1,2-dithiolene) complex [Pd(Me_2timdt)$_2$] (**1**; Me_2timdt$^{\bullet-}$ = monoreduced 1,3-dimethyl-2,4,5-trithioxoimidazolidine) with Br_2 yielded the complex [Pd(Me_2timdt)Br_2] (**2**), which was reacted with Na_2mnt (mnt^{2-} = 1,2-dicyano-1,2-ethylenedithiolate) to give the neutral mixed-ligand complex [Pd(Me_2timdt)(mnt)] (**3**). Complex **3** shows an intense solvatochromic near-infrared (NIR) absorption band falling between 955 nm in DMF and 1060 nm in $CHCl_3$ (ε = 10700 M^{-1} cm^{-1} in $CHCl_3$). DFT calculations were used to elucidate the electronic structure of complex **3** and to compare it with those of the corresponding homoleptic complexes **1** and [Pd(mnt)$_2$] (**4**). An in-depth comparison of calculated and experimental structural and vis−NIR spectroscopic properties, supported by IEF-PCM TD-DFT and NBO calculations, clearly points to a description of **3** as a dithione-dithiolato complex. For the first time, a broken-symmetry (BS) procedure for the evaluation of the singlet diradical character (DC) of heteroleptic bis(1,2-dithiolene) complexes has been developed and applied to complex **3**. The DC, predominant for **1** (n_{DC} = 55.4%), provides a remarkable contribution to the electronic structures of the ground states of both **3** and **4**, showing a diradicaloid nature (n_{DC} = 24.9% and 27.5%, respectively). The computational approach developed here clearly shows that a rational design of the DC of bis(1,2-ditiolene) metal complexes, and hence their linear and nonlinear optical properties, can be achieved by a proper choice of the 1,2-dithiolene ligands based on their electronic structure.

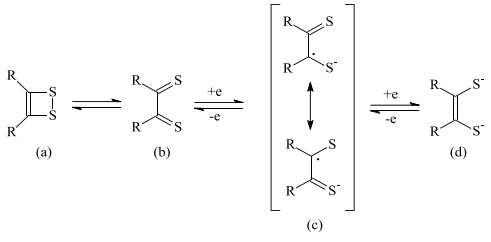


INTRODUCTION

The interest of the scientific community toward bis(1,2-dithiolene) metal complexes has been continuously increasing during the past few decades,[1−6] accompanied by a growing number of applications relying on the superconducting,[7−12] photoconducting,[13−17] magnetic, and linear and nonlinear optical properties[18−22] of this class of compounds. Bis(1,2-dithiolene) complexes $[M(R_2C_2S_2)_2]^{q-}$ of d^8 metal ions M^{x+}, such as Ni^{II}, Pd^{II}, Pt^{II}, and Au^{III}, feature peculiar properties,[5,23] such as molecular planarity and the ability to exist in well-defined oxidation states q typically ranging between $x - 4$ and $x - 2$,[24−26] also assuming fractional charges in nonintegral oxidation state (NIOS) salts.[9,12] The redox noninnocence of the 1,2-dithiolene ligands (Scheme 1) renders it difficult to partition the charge of the complexes between the ligands **L** and the central metal ion M^{x+}.[27,28]

The typical redox steps accessible to bis(1,2-dithiolene) complexes of group 10 metals (M = Ni, Pd, Pt) are summarized in Scheme 2. Dianionic bis(1,2-dithiolene) complexes $[ML_2]^{2-}$ are diamagnetic species, which can be

Scheme 1. Redox Noninnocence of 1,2-Dithiolene Ligands: Neutral 1,2-Dithiete (a) and 1,2-Dithione (b), Radical 1,2-Dithiolene Anion (c), and Dianionic Ene-1,2-dithiolate (d)



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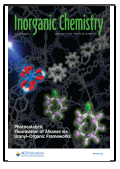

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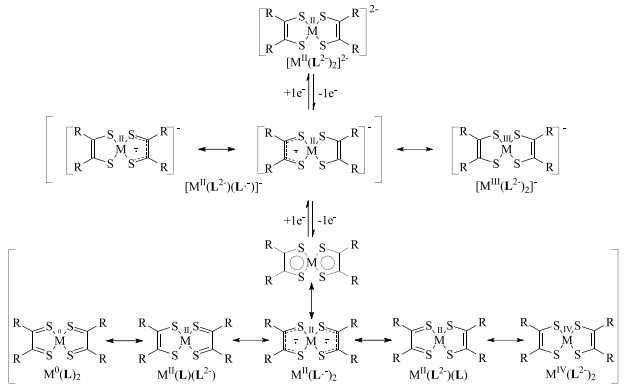
Scheme 2. Differently Charged Species and Resonance Forms of Bis(1,2-dithiolene) Metal Complexes (M = Ni, Pd, Pt; q = 0, 1, 2)



isolated as stable anions in salts such as $(Ph_4P)_2[Ni(mnt)_2]$ (mnt^{2-} = maleonitrile-1,2-dithiolate, 1,2-dicyano-1,2-ethylenedithiolate).[29] These species are fully described as $[M^{II}(L^{2-})_2]^{2-}$ complexes, featuring the ene-1,2-dithiolato form L^{2-} of the ligands (d in Scheme 1). Paramagnetic monoanionic 1,2-dithiolene complexes $[ML_2]^-$ can be represented as $[M^{III}(L^{2-})_2]^-$ compounds[30,31] or by two resonance forms showing the dianionic ligand L^{2-} (d in Scheme 1) and a monoanionic radical ligand $L^{\bullet-}$ (c in Scheme 1): i.e., $[M^{II}(L^{\bullet-})(L^{2-})]^-$.[27] In diamagnetic neutral complexes $[ML_2]$, the central metal ion can carry formal charges varying between 0 and +4, while the ligands can assume a neutral, monoanionic, or dianionic charge (Scheme 2), indicating a large degree of π-electron delocalization involving the metal as well as the L ligands (metalloaromaticity).[32] Spectroscopic and theoretical results suggest that the complexes are better described as formed by the metal dication M^{II}, whatever the charge on the complex.[27,33] Therefore, the oxidation/reduction steps leading from $[ML_2]^{2-}$ to $[ML_2]$ are mainly located on the ligands,[33−35] analogously to what has been reported for $[Au^{III}(Ar\text{-}edt)_2]^{0/-}$ complexes ($Ar\text{-}edt^{2-}$ = arylethylene-1,2-dithiolate; Ar = phenyl, 2-naphthyl, 2-pyrenyl).[36] Hence, the neutral M^{II} complexes can be described as diamagnetic singlet species formed by two antiferromagnetically coupled monoanionic radical ligands, $[M^{II}(L^{\bullet-})_2]$.[33,37] Indeed, neither the closed-shell (CS) restricted delocalized nor the localized singlet diradical description represents reliably the ground state (GS) of neutral bis(1,2-dithiolene) complexes, so that an index n_{DC} of the diradical character (DC) can be calculated to evaluate the relative weight of the diradical singlet description.[37−39] Notably, different optical properties in the visible−near-infrared (vis−NIR) region are associated with the differently charged forms of bis(1,2-dithiolene) complexes (electrochromism).[16,40,56] Neutral complexes $[ML_2]$ show a peculiar intense absorption in the region above 800 nm.[2,5,30] This band, attributed to a π−π^* HOMO → LUMO (H → L) one-electron excitation,[5,6] is shifted to lower energies and lowered in intensity in the corresponding monoreduced forms $[ML_2]^-$,[41] while the dianions $[ML_2]^{2-}$ do not show any vis−NIR absorption. In this context, for a few decades, some authors have been investigating the $[M(R'_2timdt)_2]^{q-}$ class of photoconducting[42−44] complexes ($R'_2timdt^{\bullet-}$ = monoreduced 1,3-disubstituted imidazoline-2,4,5-trithione; M = Ni, Pd, Pt; q = 0, 1, 2; Chart S1).[45−52] Neutral $[M(R'_2timdt)_2]$ complexes show a strikingly intense absorption at about 1000 nm (molar extinction coefficient ε as large as 120000 M^{-1} cm^{-1} in toluene),[48] whose energy can be fine-tuned by a proper choice of the metal M and the substituents R′.[46,48] The corresponding reduced forms show a NIR absorption falling at about 1450 nm for M = Ni, Pt and at about 1700 nm for M = Pd.[51]

Mixed-ligand bis(1,2-dithiolene) complexes $[M(L)(L')]$ have been much less investigated than homoleptic complexes[48,53] and are often prepared by metathesis reactions.[54−56] The synthetic way of obtaining $[M(L)(L')]$ complexes by replacement of halides in MLX_2 complexes has been previously reported in a few cases.[48] In these complexes, most often containing a Ni^{II} ion,[31,57−61] the most electron withdrawing "pull" ligand L tends to assume the ene-1,2-dithiolate form L^{2-} (d in Scheme 1), with shorter C−C and longer C−S bond distances, while the other "push" ligand (L′) assumes a 1,2-dithione form (b in Scheme 1), with longer C−C and shorter C−S distances, so that the complex is generally described as the dithione-dithiolato species $[M^{II}(L^{2-})(L')]$. The electronic structure of these complexes in their neutral state, reminiscent of that of diimine-dichalcogenolato complexes,[62−64] shows the HOMO featuring a larger contribution from the "pull" ligand L^{2-} and the LUMO from the "push" ligand L′. The peculiar visible−near-IR (vis−NIR) electron transition of the neutral species assumes a partial charge-transfer (CT) character from the 1,2-dithiolato L^{2-} ligand to the 1,2-dithione L′ (LL′CT), testified by a remarkable negative solvatochromism of the resulting absorption band.[54] In comparison to homoleptic complexes, the DC of heteroleptic bis(1,2-dithiolene) complexes has not been investigated, implicitly accepting that the GS configuration of these complexes is fully defined by the dithione-dithiolato CS description.[48] Nevertheless, it is conceivable that a continuous variation from ideally pure open-shell singlet diradicals $[M^{II}(L^{\bullet-})(L'^{\bullet-})]$ to CS dithione-dithiolato complexes $[M^{II}(L)(L'^{2-})]$ occurs as the difference in the donor properties of the L and L′ ligands increases. Therefore, we have considered as a case study the mixed-ligand 1,2-dithiolene Pd^{II} complex featuring the well-known mnt "pull" ligand coupled to the "push" ligand Me_2timdt. Herein, we report an experimental and theoretical investigation on the resulting complex $[Pd(Me_2timdt)(mnt)]$, in comparison with the relevant parent complexes $[Pd(Me_2timdt)_2]$ and $[Pd(mnt)_2]$, aimed at evaluating the role of the electronic structure of the ligands in tailoring the DC in homoleptic and heteroleptic bis(1,2-dithiolene) palladium complexes.

EXPERIMENTAL SECTION

Materials and Methods. Reagents were purchased from Honeywell, Alfa Aesar, and Sigma-Aldrich and used without further purification. Solvents (reagent grade) were purchased from Honeywell, VWR, and Merck and dried by using standard techniques when required. Manipulations were performed using standard Schlenk techniques under a dry dinitrogen atmosphere. Elemental analyses were performed with a CHNS/O PE 2400 series II CHNS/O elemental analyzer (T = 925 °C). FT-IR spectra were recorded with a Thermo-Nicolet 5700 spectrometer at room temperature: KBr pellets with a KBr beam splitter and KBr windows (4000−400 cm^{-1}, resolution 4 cm^{-1}) were used. Absorption spectra were recorded at 25 °C in a quartz cell of 10.00 mm optical path with either a Thermo Evolution 300 (190−1100 nm) spectrophotometer or an Agilent Cary 5000 UV−vis−NIR (190−2000 nm) dual-beam spectrophotometer. Absorption spectra were decomposed into their constituent Gaussian peaks using the Specpeak 2.0[65] and Fityk 1.3.1[66] programs. The Crystallographic Structural Database was accessed by using CCDC ConQuest 2020.1.[67]

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Inorg. Chem. 2020, 59, 17385−17401

X-ray Diffraction Measurements. Single-crystal X-ray diffraction data were collected with a Rigaku MM007/Mercury diffractometer with Mo Kα radiation. The structure was solved by direct methods with SHELXS-97[68] and refined on F^2 by using SHELXL-97.[69]

Synthesis. 1,3-Dimethyl-2-thioxoimidazolidine-4,5-dione and complex **1** were prepared according to a previously reported procedure (yield 86%).[45,46,70]

*Synthesis of [Pd(Me$_2$timdt)Br$_2$] (**2**).* [Pd(Me$_2$timdt)$_2$] (**1**; 35.4 mg; 7.27×10^{-2} mmol) was reacted with an excess of molecular dibromine in an Aldrich pressure tube using 30 mL of a $CHCl_3$/CH_3CN (2/1) solvent mixture. The glass vessel was heated to 130 °C for 15 min and slowly cooled to room temperature. The precipitate was filtered and washed with petroleum ether (brown solid; yield 32.1 mg, 97%). Mp: >230 °C. FT-IR (4000−400 cm^{-1}): ν 1477 (s), 1399 (s), 1360 (m), 1345 (m), 1291 (s), 1080 (s), 1032 (mw), 548 cm^{-1} (w). Anal. Calcd for $C_5H_6Br_2N_2PdS_3$: C, 14.10; H, 0.76; N, 8.11. Found: C, 14.86; H, 0.33; N 9.02.

*Synthesis of [Pd(Me$_2$timdt)(mnt)] (**3**).* Complex **2** (30.2 mg; 6.61×10^{-2} mmol) and a molar excess of sodium 1,2-dicyanoethylene-1,2-dithiolate (21.5 mg; 0.115 mmol) were suspended in CH_3CN (30 mL) in an Aldrich pressure tube. The mixture was heated to 130 °C for 30 min and slowly cooled to room temperature. The product was isolated as black needles by filtration, washed with water, and dried under vacuum (yield 8.3 mg, 29%). Mp: >230 °C. FT-IR (4000−400 cm^{-1}): ν 2925 (w), 2204 (m), 1459 (m), 1397 (ms), 1285 (s), 1150 (m), 1079 (ms), 864 (m), 551 (mw), 500 cm^{-1} (mw). Anal. Calcd for $C_9H_6N_4PdS_5$: C, 24.74; H, 1.38; N, 12.82. Found: C, 24.68; H, 0.45; N, 13.07.

Theoretical Calculations. Quantum-chemical calculations were carried out on $[Pd(Me_2timdt)_2]^{q-}$ (**1**$^{q-}$; Chart S2 for q = 0), [Pd(Me$_2$timdt)Br$_2$] (**2**; Chart S2), $[Pd(Me_2timdt)(mnt)]^{q-}$ (**3**$^{q-}$; q = 0, 1, 2; Chart S2 for q = 0), $[Pd(mnt)_2]^{q-}$ (**4**$^{q-}$; q = 0, 1, 2; Chart S2 for q = 0), [Pt(phen)(tdt)] (phen = 1,10-phenanthroline; tdt^{2-} = 3,4-toluenedithiolate; Chart S2),[71] and [Ni(bdt)$_2$] (bdt^{2-} = benzene-1,2-dithiolate)[33,37] and the compounds (Me$_2$timdt)$_2$ (Chart S2), Li(R′′$_2$timdt)·2THF (R′′ = 2,6-diisopropylphenyl; **5**; Chart S2),[72,73] and Me$_2$timdt(SPh)$_2$ (**7**; Chart S2)[74] at the density functional theory (DFT)[75] level with the commercial suite Gaussian 16.[76] The computational setup was validated as previously described for the strictly related [Ni(Me$_2$timdt)$_2$] complex and derivatives,[52] and it took into account three hybrid functionals (B3LYP,[77] mPW1PW,[78] and PBE0[79]) and six basis sets with relativistic effective core potentials (RECPs)[80,81] for the central metal ion (LANL08(f),[82] SBKJC,[83] Stuttgart 1997 RC,[84] CRENBL,[85] LANL2DZ,[86] and LANL2TZ[82]). DFT calculations were eventually carried out with the hybrid mPW1PW functional,[78] including a modified Perdew and Wang (PW) exchange functional coupled with the PW correlation functional.[87,88] Schäfer, Horn, and Ahlrichs double-ζ plus polarization (pVDZ)[89] all-electron basis sets for light atomic species (C, H, N, S) and CRENBL basis sets[85] with RECPs for heavier atomic species (Pd and Br) were used. Basis sets and RECPs were obtained from Basis Set Exchange and Basis Set EMSL Library.[90] Dianionic bis(1,2-dithiolene) complex species were modeled according to a closed-shell (CS) restricted description (RDFT), monoanionic paramagnetic species within an unrestricted formalism (UDFT), while neutral species were investigated (a) in their triplet ground state ($2S + 1 = 3$, two unpaired electrons), (b) in the closed-shell singlet state ($2S + 1 = 1$), or (c) as antiferromagnetically coupled singlet diradicals in a broken-symmetry (DFT-BS) approach. The last description was obtained by starting from the triplet state, with the two antiparallel electrons attributed to the two 1,2-dithiolene ligands (Chart S3 in the Supporting Information). The BS electron density guess was obtained through a fragment approach (*guess* = *fragment* = 3, the three fragments being the Pd^{II} ion and the two monoanionic 1,2-dithiolene radical ligands), eventually allowing optimization (*opt*) of the geometry of the complex (BS1 solution). Finally, only in the case of **1**, the guess of the electron density of the lowest BS singlet excited state (ES) was used to reoptimize the geometry of the GS electronic structure of the complex, giving an alternative minimum for the BS GS configuration (BS2), degenerate with respect to the BS1 description ($|\Delta\varepsilon_{BS2-BS1}| \approx 8 \times 10^{-4}$ hartree).

For all compounds, tight SCF convergence criteria and fine numerical integration grids (*grid* = *ultrafine*) were used. In order to evaluate the singlet diradical contribution to the GS in the BS approach, the differences between the total electronic energy of the singlet state (ε_S), the BS-singlet state (ε_{BS}), and the triplet (ε_T) states were considered:[38,91,92]

$$\varepsilon_1 = \varepsilon_{BS} - \varepsilon_S \tag{1}$$

$$\varepsilon_2 = \varepsilon_T - \varepsilon_S \tag{2}$$

The effective electron exchange integrals J_{ab}[93] were calculated as follows:

$$J_{ab} = \frac{\varepsilon_1 - \varepsilon_2}{\langle S^2\rangle_T - \langle S^2\rangle_{BS}} = \frac{\varepsilon_{BS} - \varepsilon_T}{\langle S^2\rangle_T - \langle S^2\rangle_{BS}} \tag{3}$$

where $\langle S^2\rangle_T$ and $\langle S^2\rangle_{BS}$ represent the spin expectation values[94,95] determined at the optimized geometry for the triplet and broken-symmetry GSs, respectively, after verification of the wave function stability (*stable* = *opt*). The singlet−triplet energy gap $\Delta\varepsilon_{ST}^{SC} = \varepsilon_S^{SC} - \varepsilon_T$, accounting for the effect of spin contamination to the energy of the singlet GS,[95] corresponding to a mixing of the singlet and triple state, was calculated as

$$\Delta\varepsilon_{ST}^{SC} = \Delta\varepsilon_{ST}\frac{\langle S^2\rangle_T}{\langle S^2\rangle_T - \langle S^2\rangle_{BS}}$$

Therefore, the ε_S^{SC}value was obtained:

$$\varepsilon_S^{SC} = \varepsilon_T + \Delta\varepsilon_{ST}\frac{\langle S^2\rangle_T}{\langle S^2\rangle_T - \langle S^2\rangle_{BS}} \tag{4}$$

The diradical character index n_{DC} can be directly calculated from $\langle S^2\rangle_{BS}$:[17,37]

$$n_{DC} = 1 - \sqrt{1 - \langle S^2\rangle_{BS}} \tag{5}$$

A complete natural population analysis (NPA) was carried out with a natural bonding orbital (NBO)[96] partitioning scheme (*pop* = *nboread*, with *boao* and *bndidx* keywords in the NBO section of the input file) in order to investigate the charge distributions and Wiberg bond indexes.[97] Absorption vertical transition energies and oscillator strengths were calculated at the time-dependent (TD) DFT level.[98,99] TD-DFT calculations were carried out at the optimized geometry in the gas phase and in a selection of solvents ($CHCl_3$, CH_2Cl_2, DMF, THF, acetonitrile), implicitly taken into account by means of the polarizable continuum model in its integral equation formalism (IEF-PCM),[100] describing the cavity of the complexes within the reaction field (SCRF) through a set of overlapping spheres. Oscillator strength values calculated at the TD-DFT level along with experimental full width at half maximum (FWHM) values of the NIR band were used to evaluate the molar extinction coefficients ε.[101] Experimental FWHM values on an energy scale (eV) were evaluated from the corresponding values w determined in nm from the experimental NIR spectra:

$$W = 10^7\frac{w}{\lambda_0^2 - \frac{1}{4}w^2}$$

The one-photon absorption oscillator strength f_{0n} for each transition $0 \rightarrow n$ is[102]

$$f_{0n} = \frac{8\pi^2 m_e \nu_{0n}|\mu_{0n}|^2}{3e^2h}$$

where m_e and e are the mass and the charge of the electron, ν_{0n} is the frequency (s^{-1}) of the transition between the states 0 and n, μ_{0n} is the transition dipole moment, and h is Planck's constant. f_{0n} is related to the experimental intensity of each absorption band:

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Inorg. Chem. 2020, 59, 17385−17401

$$f_{0n} = 4.32 \times 10^{-9} \int \varepsilon(\varpi)\, d\varpi$$

where ε is the molar extinction coefficient (M^{-1} cm^{-1}) and ϖ is the frequency (cm^{-1}). By adoption of Gaussian curve shapes for the absorption bands

$$f_{0n} = 4.32 \times 10^{-9} \varepsilon \int e^{-(\Delta\varpi/\theta)^2}\, d\varpi$$

$$f_{0n} = 4.32 \times 10^{-9} \sqrt{\pi}\, \varepsilon\theta$$

where the width parameter θ is related to W by

$$\theta = \frac{W}{2\sqrt{\ln 2}}$$

Therefore, the equation

$$\varepsilon_{calc} = \frac{2\sqrt{\ln 2}}{4.32 \times 10^{-9}\sqrt{\pi}} \frac{f_{0n}}{W} \quad (6)$$

allows evaluating the molar extinction coefficients of the NIR transition at the TD-DFT level. Calculated molar extinction coefficients were scaled on experimental available data to give a corrected $\varepsilon_{calc}^{corr}$ value.

The nature of the minima of each structure optimized at the DFT and DFT-BS levels was verified by harmonic frequency calculations (*freq = raman*), including the determination of thermochemistry parameters (zero-point energy (ZPE) corrections and thermal corrections to enthalpy and Gibbs free energy) and the calculation of FT-Raman frequencies. Gibbs free energies were used to calculate absolute reduction potentials at 298 K (E_{Abs}^{298K}) according to the following equation:[103−106]

$$E_{Abs}^{298K} = \frac{\Delta G_{neutral}^{298K} - \Delta G_{anion}^{298K} - \Delta G_e^{\circ}}{F} \quad (7)$$

where $\Delta G_{neutral}^{298K}$ and ΔG_{anion}^{298K} are the free energy values calculated at 298 K and $\Delta G_e^{\circ}/F$ represents the potential of the free electron (−0.03766 eV at 298 K; $\Delta G_{neutral}^{298K}$ is calculated on the most stable neutral form).[107] E_{Abs}^{298K} values were also referenced to the Fc^+/Fc couple, taken into account at the same level of theory.

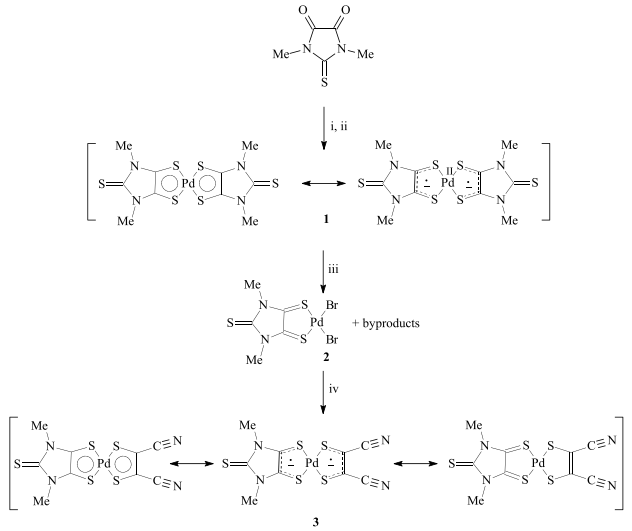
The total static (i.e., under zero frequency)[108] second-order (quadratic) hyperpolarizability (the first hyperpolarizability)[109] β_{tot} was calculated as previously described.[110]

Throughout all this work, molecules in their optimized standard orientation were rotated in order to align the main symmetry axis (bisecting C−C 1,2-dithiolene bonds and passing through the central metal ion) with the *z* axis and lie on the *yz* plane. Molden 6.2[111] and GaussView 6.0.16[112] were used to analyze Kohn−Sham (KS) molecular orbital (MO) compositions and energies. GaussSum 3.0[113] and Chemissian 4.54[114] were used to evaluate the atomic orbital contributions to KS-MOs and to analyze TD-DFT data.

RESULTS AND DISCUSSION

Synthesis. The synthesis of $[Pd(R'_2timdt)_2]$ neutral complexes can be achieved by direct sulfuration with Lawesson's reagent (2,4-bis(4-methoxyphenyl)-1,3,2,4-dithiadiphosphetane-2,4-disulfide)[115] of the corresponding 1,3-disubstituted 2-thioxoimidazolidine-4,5-diones, followed by addition of $PdCl_2$ (reactions i and ii in Scheme 3).[45,46] The reaction of a suspension of $[Pd(Me_2timdt)_2]$ (**1**) in a 2/1 $CHCl_3/CH_3CN$ solvent mixture with a molar excess of molecular dibromine in a high-pressure tube at 130 °C yielded the neutral complex $[Pd(Me_2timdt)Br_2]$ (**2**; reaction iii in Scheme 3), which was successively made to react with sodium 1,2-dicyanoethylene-1,2-dithiolate (Na_2mnt) in $CHCl_3$ at 130 °C to give the mixed-ligand neutral complex $[Pd(Me_2timdt)(mnt)]$ (**3**; reaction iv in Scheme 3).

Scheme 3. Reaction Pathways for the Synthesis of 3[a]



[a]Legend: (i) Lawesson's reagent, refluxing toluene, N_2; (ii) $PdCl_2$; (iii) Br_2, $CHCl_3/CH_3CN$ 2/1, 130 °C; (iv) Na_2mnt, CH_3CN, 130 °C.

X-ray Diffraction Studies. Tiny needle crystals of **3**, suitable for a structural characterization by X-ray diffraction analysis (Figure 1, Tables S1−S6, and Figures S1 and S2),

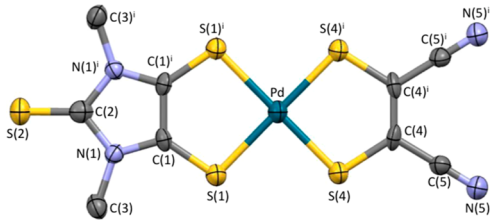


Figure 1. ORTEP view of complex **3** with the adopted labeling scheme. Selected bond distances (Å) and angles (deg): Pd−S(1) 2.314(2), C(1)−S(1) 1.660(8), C(1)−C(1)^i 1.454(16), C(1)−N(1) 1.342(9), N(1)−C(3) 1.454(10), N(1)−C(2) 1.401(10), C(2)−S(2) 1.603(13), Pd−S(4) 2.258(2), C(4)−S(4) 1.724(8), C(4)−C(4)^i 1.364(16), C(4)−C(5) 1.423(11), N(5)−C(5) 1.139(10) Å; S(1)−Pd−(S1)^i 91.53(12), S(1)−Pd−(S1)^i 90.61(12), S(1)−Pd−S(4) 88.92(8), C(1)−S(1)−Pd−S(4) 179.6(2), S(1)−Pd−S(4)−C(4) 177.3(2). Displacement ellipsoids are drawn at the 30% probability level. Hydrogen atoms are omitted for clarity. Symmetry operation: (i) *x*, 1/2 − *y*, *z*.

were isolated from the reaction mixture. The structural features of **3** (Figure 1) closely resemble those determined previously for $[Pd(Et_2timdt)(mnt)]$.[48] The molecule is planar except for the methyl substituents, with the central Pd ion coordinated by the two 1,2-dithiolene ligands in a pseudo-square-planar fashion, with unbalanced Pd−S bond distances (Pd−S(1), 2.314(2); Pd−S(4), 2.258(2) Å). The C(1)−C(1)^i bond length within the Me_2timdt ligand (1.454(16) Å) is longer than that previously reported for $[Pd(Et_2timdt)_2]$ (1.397(9) Å),[45] while the C(1)−S(1)/C(1)^i−S(1)^i distances (1.660(8) Å) are shorter (corresponding average value in $[Pd(Et_2timdt)_2]$ 1.689(8) Å), suggesting a larger character of ene-1,2-dithiolate of the Me_2timdt ligand in **3** as compared to the Et_2timdt ligands in $[Pd(Et_2timdt)_2]$. When the two C_2S_2Pd metallacycles in **3** are compared, the C(4)−C(4)^i length in the mnt unit (1.364(16) Å) is shorter than that in the Me_2timdt unit, while the C−S distances are longer in the mnt ligand

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Inorg. Chem. 2020, 59, 17385−17401

(C(4)−S(4) 1.724(8) Å). The C−C distance in the Me_2timdt ligand of **3** (1.454(16) Å) is intermediate between the corresponding distance in [Pd(Et_2timdt)Br_2] (1.474(10) Å; Chart S2),[48] featuring an authentic neutral Et_2timdt ligand, and that of Li(**5**, R″ = 2,6-diisopropylphenyl, Chart S2; 1.417(4) Å), featuring the R″$_2$timdt$^{\bullet-}$ radical monoanion.[72,73] Analogously, the C(4)−C(4)^{i} distance in **3** (1.364(16) Å) is shorter than that found in [Pd($mnt)_2$] (**4**; 1.39(2) Å; Chart S2)[116] and the average value for **4**$^{-}$ monoanions (1.377(24) Å)[117] but slightly larger than the average value found in salts of the complex **4**$^{2-}$ (1.359(19) Å).[118] This suggests that the Me_2timdt ligand in **3** should be considered to carry a partial negative charge and that the GS of **3** should include a partial DC. The unit cell contains pairs (Z = 2) of symmetry-related complex molecules, each forming slipped stacks along the a vector (Figures S1 and S2 in the Supporting Information) with an interplanar distance of 3.619 Å, very close to that featured by the stacks found in the crystal structure of [Pd(Et_2timdt)$_2$] (3.6 Å).[45] Along the stacks, the terminal thione groups of the Me_2timdt ligands weakly interact with the π-system of the imidazoline ring (C(1)$^{ii/iii}$−S(2) 3.420 Å; (ii) $-1+x, y, z$; (iii) $-1+x, 1/2-y, z$; Figure S1). Weak contacts between the methyl substituents at the Me_2timdt ligands and the terminal N atoms of the mnt ligands (H(3A)···N(5)^{iv} 2.644 Å; (iv) $-1+x, y, 1+z$) are responsible for the interactions between adjacent stacks aligned along the c direction. Notably, the crystal packing is sensibly different from that found in [Pd(Et_2timdt)(mnt)], where the complex molecules are stacked in an alternate head-to-tail disposition, allowing for shorter interplanar distances (3.570 Å).[48]

Absorption Spectroscopy. Neutral [Pd(R′$_2$timdt)$_2$] bis(1,2-dithiolene) complexes featuring alkyl R substituents show a peculiar, intense NIR absorption falling at about 1010 nm, with molar extinction coefficients ε as high as 70000 M^{-1} cm^{-1} in CH_2Cl_2.[45,46] The UV−vis−NIR absorption spectrum of a CH_2Cl_2 solution of **1** shows a NIR absorption maximum falling at 1008 nm (full width at half-maximum (FWHM) w = 131 nm; Figure S3). Notably, the NIR peak shows at least three Gaussian components (λ_1 = 1004.8 nm, w_1 = 121.9 nm, integral ratio 74.5%; λ_2 = 890.3 nm, w_2 = 93.5 nm, 6.6%; λ_3 = 1120.2 nm, w_3 = 155.4 nm, 18.9%; Figure S3),[65] in agreement with the spectral decomposition reported for [Pd(2,4-$^{t}Bu_2C_6H_2S_2)_2$], for which a series of d−d transitions with different spin couplings to the open-shell ligands were envisaged.[33] Complex **3** shows a well-defined intense NIR peak at 1060 nm in $CHCl_3$ (ε = 10700 M^{-1} cm^{-1}; Figure 2), in perfect agreement with the spectral features shown by [Pd(Et_2timdt)(mnt)] in the same solvent (λ_{max} = 1061 nm, ε = 12500 M^{-1} cm^{-1}).[48] The NIR band can be decomposed into two main peaks, each accounting for about half the area of the band (λ_1 = 1066.2 nm, w_1 = 140.6 nm, 51.6%; λ_2 = 1025.1 nm, w_2 = 249.5 nm, 48.4% in $CHCl_3$; Figures S4 and S5). The NIR band displays a remarkable negative solvatochromism, with absorption maxima wavelengths ranging between 955 nm in DMF and 1060 nm in $CHCl_3$ (Table 1). When the solvent polarity is increased, the change in the experimental spectral shapes (Figure S6) suggests that the relative weight and the energy difference between the red component and the main peak of the solvatochromic NIR band increases, so that a greater polar nature should be attributed to the higher energy peak as compared to the main peak.

Theoretical Calculations. During the past few decades, DFT calculations have been used successfully to investigate the structural features and the redox and spectroscopic properties of homoleptic and heteroleptic complexes containing 1,2-dithiolene ligands.[36−39,48,50,52,62,64,72] DFT calculations were applied here on Me_2timdt^{q-}, mnt^{q-} (q = 0, 1, 2), and related compounds and the relevant neutral, monoanionic, and dianionic homoleptic and heteroleptic Pd complexes.

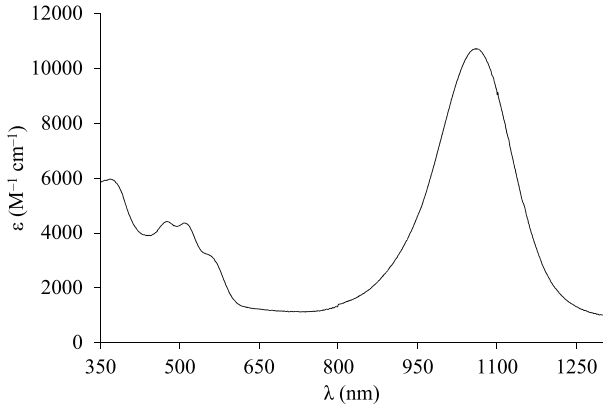

Figure 2. UV−vis−NIR absorption spectrum (350−1300 nm) of **3** in $CHCl_3$ solution.

Ligands. The relative stability of the variously charged forms of 1,2-dithiolene ligands (Scheme 1) depends on the nature of the R substituents. The mnt ligand is generally encountered in its 1,2-dithiolate form, and the corresponding neutral species is unreported. In fact, neutral 1,2-dithiolene species are generally unstable,[6] but depending on the R substituents they can be found as either 1,2-dithiones (Scheme 1, b), for instance embedded in 1,2-dithioxamides,[119] or stabilized as 1,2-dithietes (Scheme 1, a).[120−122] Since vicinal dithioxamides in five-membered rings are reportedly unstable,[123] R′$_2$timdt ligands cannot be isolated as neutral 2,4,5-trithiones and the sulfuration of disubstituted 2-thioxomidazolidine-4,5-diones leads to tetrasubstituted 4,5,6,7-tetrathiocino[1,2-b:3,4-b']diimidazolyl-2,9-dithione or 4,5,9,10-tetrathiocino[1,2-b:5,6-b']-2,7-dithione (a and b in Chart S4 in the Supporting Information, respectively), the latter type of compounds being the final product of the Br_2 oxidation of [Pd(R′$_2$timdt)$_2$] complexes (R′ = Et).[124] The only example of an authentic radical monoanion R″$_2$timdt$^{\bullet-}$ has been isolated in compound **5**.[72] Neutral 1,2-dithiolene ligands stabilized in the form of 3,4-disubstituted 1,2-dithietes have been characterized in few cases (R = CF_3,[120] $COOCH_3$,[121] 1-adamantyl[122]). An examination of the ZPE-corrected total electronic energies ε^0_{ZPE} of the neutral 1,2-dithiolene ligands in the dithione and dithiete forms (Table 2) shows that the dithiete form is more favored for the mnt ligand in comparison to the Me_2timdt ligand (ε^0_{ZPE} = 16.28 and −42.58 kcal/mol, respectively). A comparison of the C−C bond distances calculated for Me_2timdt^{q-} (d_{C-C} = 1.500, 1.434, and 1.394 Å for q = 0, 1, and 2, respectively; Table 2) can be made with the corresponding bond distances determined structurally in [Pd(Et_2timdt)Br_2] (average d_{C-C} value 1.47(1) Å; q = 0; Chart S2), **5** (d_{C-C} = 1.417(4) Å, q = 1; Chart S2),[48] [**6**·2Br]$^{2+}$(Br_2)$_2$(Br_2)$_3$ (**6** = 4,5,9,10-tetrathiocino[1,2-b:5,6-b']-1,3,6,8-tetraethyldiimidazolyl-2,7-dithione; d_{C-C} = 1.37(2) Å, q = 2; Chart S2), and 1,3-dimethyl-4,5-bis(phenylsulfanyl)-1,3-dihydro-2*H*-imidazole-2-thione (**7**, d_{C-C} = 1.361(6) Å, q = 2; Chart S2).[74] As expected, on passing from dianions to the corresponding neutral species the C−C bond lengths increase

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Inorg. Chem. 2020, 59, 17385−17401

Table 1. Experimental NIR Absorption Maximum Wavelengths λ (nm), Energies E (eV), and FWHM Values w on a Wavelength Scale (nm) Recorded for 3, in Comparison with the Corresponding Values λ_{calc} and E_{calc} Calculated at the TD-DFT IEF-PCM Level (CS GS) and Calculated Oscillator Strengths f, Extinction Coefficients $\varepsilon^{corr}_{calcd}$ (M^{-1} cm^{-1}), and HOMO−LUMO Energy Gaps ΔE_{H-L} (eV) in Selected Solvents

	λ	λ_{calc}	E	E_{calc}	w	f	$\varepsilon^{corr}_{calc}$	ΔE_{H-L}
$CHCl_3$	1060	876.0	1.167	1.416	180	0.385	10700	1.68
CH_2Cl_2	1020	863.8	1.216	1.436	151	0.368	11895	1.73
THF	1011	864.4	1.226	1.435	168	0.368	10675	1.71
CH_3CN	966	843.9	1.284	1.469	236	0.340	6630	1.77
DMF	955	851.8	1.298	1.456	217	0.356	7712	1.77

Table 2. Optimized C−C and C−S Bond Distances (d_{C-C} and d_{C-S}, Å) within the 1,2-Dithiolene Moiety and Corresponding Wiberg Bond Indices (WBI_{C-C} and WBI_{C-S}), Variations in ZPE Corrected Total Electronic Energies ($\varepsilon^0_{ZPE} = \varepsilon^0$ + ZPE, kcal mol^{-1}), Sum of Electronic Energies and Thermal Enthalpies (H_{corr}, kcal mol^{-1}), and Free Energies (G_{corr}, kcal mol^{-1}) Calculated for the 1,2-Dithiolene Ligands mnt^{q-} and Me_2timdt^{q-} (q = 0, 1, 2)

	q	d_{C-C}	d_{C-S}	WBI_{C-C}	WBI_{C-S}	$\Delta\varepsilon^0_{ZPE}$	$\Delta(\varepsilon^0 + H_{corr})$[c]	$\Delta(\varepsilon^0 + G_{corr})$[d]
mnt[a]	0	1.501	1.625	1.018	1.787			
mnt[b]	0	1.371	1.756	1.501	1.100	−16.28[e]	−16.58[e]	−15.46[e]
Me_2timdt[a]	0	1.500	1.629	1.007	1.712			
Me_2timdt[b]	0	1.343	1.765	1.538	1.061	42.58[e]	41.28[e]	45.27[e]
mnt^-	1	1.431	1.681	1.397	1.235	−84.47[f]	−84.58[f]	−84.09[f]
Me_2timdt^-	1	1.434	1.675	1.217	1.423	−51.33[f]	−51.35[f]	−50.90[f]
mnt^{2-}	2	1.406	1.736	1.365	1.178	−34.75[f]	−34.87[f]	−33.87[f]
Me_2timdt^{2-}	2	1.394	1.738	1.453	1.201	13.09[f]	13.07[f]	14.23[f]

[a]1,2-Dithione form. [b]1,2-Dithiete form. [c]Sum of electronic and thermal enthalpies. [d]Sum of electronic and thermal free energies. [e]Relative energy difference between the 1,2-dithiete and the 1,2-dithione form: $\Delta\varepsilon^0 = \varepsilon^0$(dithiete) − ε^0(dithione). [f]Relative energy difference between reduced and neutral species: $\Delta\varepsilon^0 = \varepsilon^0$(reduced) − ε^0(neutral)

and the C−S distances decrease. It is worth noting that mnt^{q-} and Me_2timdt^{q-} (q = 0, 1, 2) share closely related frontier MO compositions (Figures S7 and S8). For both ligands, the KS-HOMO-1 and KS-HOMO of neutral species **L** are nonbonding molecular orbitals (NBMOs) built up from the in-phase and out-of-phase combinations, respectively, of the sulfur 3p AOs lying on the ligand plane. The LUMO is a π-in-nature MO derived from the combination of C $2p_z$ and S $3p_z$ AOs of the ene-1,2-dithiolate system, bonding with respect to the C−C bond and antibonding with respect to the C−S bonds. The LUMO of neutral **L** ligands becomes the SOMO and the HOMO in monoanionic $\mathbf{L}^{\bullet-}$ and dianionic $\mathbf{L}^{2-}$ species, respectively (Figures S7 and S8). The absolute reduction potential[105,125,126] E^{298K}_{Abs} (eq 7) of the redox step $\mathbf{L}/\mathbf{L}^{\bullet-}$ increases on passing from Me_2timdt to mnt (2.245 and 3.014 V, respectively), indicating that the mnt ligand displays the largest tendency to reduction. The difference in the E^{298K}_{Abs} values for the $\mathbf{L}/\mathbf{L}^{\bullet-}$ and $\mathbf{L}'/\mathbf{L}'^{\bullet-}$ couples, which only depends on the choice of the substituents R at the ene-1,2-dithiolate, can be considered a useful parameter to evaluate the "push" and "pull" nature[48,54] of 1,2-dithiolene ligands in heteroleptic mixed-ligand metal complexes [M(**L**)(**L**′)].

Diradical Character (DC) in Bis(1,2-dithiolene) Complexes. The ground state (GS) of neutral bis(1,2-dithiolene) complexes is characterized by a significant degree of DC,[33−37] due to the very narrow HOMO−LUMO energy gap ΔE_{H-L} that renders the singlet and triplet GSs very close in energy. In a pure diradical the nonbonding molecular orbitals (NBMOs) ψ_a and ψ_b hosting the two electrons at the highest energy are degenerate, being localized on the two different ligands in bis(1,2-dithiolene) metal complexes,[127] and they have consequently a negligible overlap integral $S_{ab} = \langle\psi_a|\psi_b\rangle$. Under these conditions, the two possible spin states, i.e. singlet ($2S + 1 = 1$) and triplet ($2S + 1 = 3$), are degenerate, their energy difference $\Delta\varepsilon_{ST} = \varepsilon_S - \varepsilon_T$ being related to the exchange interaction $J = 1/2(\varepsilon_S - \varepsilon_T) = 1/2\Delta\varepsilon_{ST}$.[91] When S_{ab} is not negligible and the two NBMOs are quasi-degenerate, the triplet configuration is the most stable ($\varepsilon_S > \varepsilon_T$) and J assumes positive values in the so-called diradicaloids or diradical-like compounds. Wirz proposed discriminating between diradicals and diradicaloids depending on the singlet−triplet energy gaps ($\Delta\varepsilon_{ST} \leq 10$ and 100 kJ mol^{-1} for diradicals and diradicaloids, respectively).[128] When the energy difference between the two involved MOs is larger and a significant gap exists, the energy stabilization competes with the electron−electron exchange interaction, and the CS singlet GS becomes progressively more stable. The theoretical evaluation of the GS in diradical and diradicaloid species is a challenging task, which requires the evaluation of the stability of the triplet and singlet GSs of the investigated compound. The triplet GS can generally be calculated by theoretical methods with unrestricted wave functions, such an unrestricted HF (UHF) or density functional theory (UDFT). The modeling of open-shell singlet diradicals requires multireference approaches: for instance, multireference coupled-cluster calculations, such as Mk-CCSD(T),[129] complete active-space self-consistent field (CASSCF),[94] or the complete-active-space second-order perturbation theory (CASPT2).[130] In fact, although they are computationally very efficient, DFT calculations cannot accurately describe open-shell singlet states of diradicals, so that $\Delta\varepsilon_{ST}$ and hence J values are largely uncertain. The broken-symmetry (BS) DFT (DFT-BS) spin-unrestricted reference configuration with antiparallel spins has been proposed as a compromise to extend UDFT calculations to diradical species,[91,131−135] by correcting J and $\Delta\varepsilon_{ST}$ for spin contamination[94,133,134] that affects the expectation value of

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Table 3. Optimized Pd−S, C−C, and C−S Bond Lengths (d, Å) and Wiberg Bond Indices (WBI) within the 1,2-Dithiolene Ligands L and L′ of $[Pd(L)(L')]_2^{q-}$ Complexes (L = L′ = Me_2timdt for 1^{q-}; L = Me_2timdt, L′ = mnt for 3^{q-}; L = L′ = mnt for 4^{q-}; q = 0, 1, 2)[a]

			L					L′				
	GS	symm[b]	d_{Pd-S}	d_{C-C}	d_{C-S}	WBI_{C-C}	WBI_{C-S}	d_{Pd-S}	d_{C-C}	d_{C-S}	Δd_{C-C}[c]	WBI_{C-C}	WBI_{C-S}
1	triplet	$^3B_{1u}$	2.351	1.410	1.698	1.177	1.378						
	singlet	^1A_g	2.314	1.404	1.697	1.269	1.276						
	BS		2.307	1.401	1.699	1.251	1.274						
$[Pd(Et_2timdt)_2]$ (structural data)[d,e]			2.295(2)	1.397(9)	1.689(8)								
$\mathbf{1}^-$	doublet	$^2B_{2g}$	2.337	1.381	1.717	1.385	1.192						
$\mathbf{1}^{2-}$	singlet	^1A_g	2.376	1.365	1.739	1.482	1.126						
3	triplet	$^3B_1$	2.359	1.408	1.700	1.226	1.267	2.305	1.404	1.701	0.004	1.307	1.098
	singlet	$^1B_1$	2.342	1.428	1.674	1.168	1.397	2.263	1.393	1.725	0.035	1.417	1.098
	BS	–	2.344	1.422	1.682	1.186	1.354	2.273	1.389	1.717	0.033	1.384	1.098
3 (structural data)[f]			2.314(2)	1.454(16)	1.660(8)			2.258(2)	1.364(16)	1.724(8)	0.090		
$\mathbf{3}^-$	doublet	$^2A_1$	2.369	1.397	1.697	1.290	1.276	2.286	1.376	1.740	0.021	1.451	1.138
$\mathbf{3}^{2-}$	singlet	$^1B_1$	2.384	1.364	1.737	1.477	1.131	2.323	1.381	1.744	−0.017	1.424	1.130
4	triplet	$^3B_{1u}$	2.325	1.410	1.696	1.277	1.329						
	singlet	^1A_g	2.275	1.403	1.701	1.325	1.305						
	BS		2.289	1.451	1.699	1.311	1.312						
$\mathbf{4}^-$	doublet	$^2B_{2g}$	2.295	1.386	1.725	1.405	1.195						
$\mathbf{4}^{2-}$	singlet	^1A_g	2.332	1.380	1.743	1.428	1.131						
4 (structural data)[e,g]			2.263(7)	1.39(2)	1.71(1)								

[a]For neutral species (q = 0), the distances in the open-shell paramagnetic triplet, CS diamagnetic singlet, and singlet diradical (BS) configurations are reported. [b]GS-symmetry representations are referenced to the D_{2h} (**1**, **4**) and C_{2v} (**3**) point groups, with the complex molecule laying on the yz plane and the main axis being coincident with z. [c]Δd_{C-C} = difference in d_{C-C} values calculated within the two ligands $Me_2timdt^{-q/2-1}$ and $mnt^{-q/2-1}$ in $\mathbf{3}^{q-}$. [d]Reference 45. [e]Average value. [f]This work. [g]Isolated in $(perylene)_2$(**4**). Reference 116.

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Inorg. Chem. 2020, 59, 17385−17401

the total spin $\langle S^2 \rangle$ with respect to $\langle S(S+1) \rangle$.[94,95,136] In different studies, the DC index n_{DC} of homoleptic bis(1,2-dithiolene) complexes was evaluated. A comparison of n_{DC} calculated at different levels of theory suggests that the DFT-BS approach underestimates the DC of bis(1,2-dithiolene) metal complexes. In fact, the DC of the neutral complex $[Ni(bdt)_2]$ (bdt^{2-} = benzene-1,2-dithiolate) was calculated to be as large as 69.1% at the CASSCF level,[37] 32% at the ZORA-SORCI level (ZORA = zeroth-order regular approximation; SORCI = spectroscopy oriented configuration interaction),[33] and 17.2% at the DFT-BS level. The DC depends not only on the 1,2-dithiolene ligand but also on the nature of the central metal ion. In the series of complexes of M^{II} ions derived from the 3,5-di-*tert*-butyl-1,2-benzene-dithiolato ligand, the n_{DC} values were calculated to be 32%, 50%, and 30% for M = Ni, Pd, Pt, respectively,[33] suggesting that Pd^{II} species may show particularly stable singlet diradicals in comparison to the corresponding Ni^{II}/Pt^{II} analogues.

Homoleptic Bis(1,2-dithiolene) Complexes. Members of the class of complexes $[M(R'_2timdt)_2]^{q-}$ (M = Ni, Pd, Pt; q = 0, 1, 2) are mostly stable as neutral species, and quite severe conditions are needed to achieve a reversible chemical or electrochemical reduction to the corresponding monoanionic radical species.[16,46,48,52] With regard to M = Pd, while the crystal structures of $[Pd(Et_2timdt)_2]$ and the CT adduct $[Pd(Et_2timdt)_2]\cdot I_2\cdot CHCl_3$ have long since been published,[45] no anionic complexes $[Pd(R'_2timdt)_2]^{-/2-}$ have been structurally characterized so far. Conversely, neutral $[M(mnt)_2]$ complexes (M = Ni, Pd, Pt) are extremely rare, and $(perylene)_2$(**4**) is the only compound characterized structurally incorporating the neutral species **4**,[116] while to date 37 examples of compounds incorporating the anions $\mathbf{4}^{-/2-}$ have been deposited with the Cambridge Crystallographic Database.[137] Accordingly, **1** is calculated to be sensibly more stable to reduction in the gas phase and in CH_2Cl_2 than **4** (E^{298K}_{Abs} = 3.057 and 4.349 eV for complex **1** and 4.786 and 5.752 eV for complex **4**, in the gas phase and in CH_2Cl_2, respectively). In Table 3, the metric parameters optimized for the bis(1,2-dithiolene) complexes $\mathbf{1}^{q-}$ and $\mathbf{4}^{q-}$ (q = 0, 1, 2) are summarized. In the case of neutral complexes (q = 0), the geometry was optimized (i) for the singlet CS (RDFT), (ii) for the triplet open-shell (UDFT), and (iii) for the singlet diradical (DFT-BS) GS configurations. The total electronic energy ε_T of the $^3B_{1u}$ triplet state is calculated to be lower by about 2.4 kcal mol^{-1} (10 kJ mol^{-1}) in comparison to that (ε_S) of the uncorrected singlet ^1A_g GS ($\varepsilon_2 < 0$, eq 2), thus classifying **1** as a diradical species.[128] In fact, the DFT-BS GS of **1** shows a large $\langle S^2 \rangle_{BS}$ value (0.80, Table 4), indicating a considerable spin contamination from the triplet state.[94] An evaluation of the total electronic energy of the BS GS shows that it is the most stable configuration in comparison to both the triplet and CS-singlet configurations (eq 1), reflected by the diradical character n_{DC} = 55.4% (Table 4, eq 5). The singlet GS calculated for **4** is sensibly lower in energy in comparison to the relevant triplet state (Table 4), indicating a diradicaloid character. Accordingly, the singlet diradical configuration is only slightly more stable than the uncorrected CS singlet state and has an $\langle S^2 \rangle_{BS}$ value smaller than 0.5. In fact, the spin-contamination corrected state (eq 4) was found to be the most stable state with only a partial diradical character (n_{DC} = 27.5%, Table 4). A comparison between structural and DFT-optimized bond distances for complexes **1** and **4** shows that the Pd−S and C−C distances are slightly overestimated, while C−S bond lengths are very close. Pd−S bond lengths are very sensitive to the GS configuration and follow the trend Pd−S (triplet) > Pd−S (CS singlet) ≥ Pd−S (singlet diradical) > Pd−S (structure). The C−S bond distances optimized for the singlet diradical GSs of **1** and **4** (1.699 Å; Table 3) are very close to those calculated for the hypothetical free $Me_2timdt^{\bullet-}$ and $mnt^{\bullet-}$ radical anions (1.681 and 1.675 Å, respectively) but remarkably different from those calculated for the relevant 1,2-dithiones and 1,2-dithiolates (Table 2). This supports the description of neutral homoleptic complexes as $[Pd(L^{\bullet-})_2]$ for both classes of complexes. Although the agreement between structural and optimized C−C distances is less accurate in comparison to C−S bond lengths, the former values are affected very greatly by the charge on the ligands. In Figure 3, the optimized C−C distances and the corresponding Wiberg bond indices (WBIs)[97] are compared for a variety of R'_2timdt derivatives showing a C=C double bond, as in 4,5,9,10-tetrathiocino[1,2-*b*:5,6-*b*′]diimidazolyl-1,3,6,8-tetramethyl-2,7-dithione $(Me_2timdt)_2$ and compound **7**,[74] or a single bond, as in the neutral complex **2** and in compound **5** (Chart S2).[72,73] For these compounds, a clear correlation (R^2 = 0.99) holds between the optimized C−C bond distance d_{C-C} within the R_2timdt ring and the corresponding WBI_{C-C} values. This clearly shows that WBIs calculated at the optimized distances

Table 4. Energy Differences (kcal mol^{-1}) between the Singlet and the Broken−Symmetry Configurations (ε_1), the Singlet and the Triplet Configurations (ε_2), the Spin Contamination Corrected Singlet and the Triplet Configurations ($\Delta\varepsilon_{ST}^{SC}$), Expectation Value of the Spin Contaminant $\langle S^2 \rangle_{BS}$ for the Singlet Diradical Configuration, Effective Electron Exchange Integrals J_{ab} and Diradical Characters n_{DC} (%) Calculated for Complexes 1, 3, and 4

	1	3	4
ε_1	−4.325	−0.789	−1.015
ε_2	−2.404	5.817	6.197
$\Delta\varepsilon_{ST}^{SC}$	3.986	−7.420	−8.096
$\langle S^2 \rangle_{BS}$	0.801	0.436	0.474
$\lvert J_{ab} \rvert$	1.579	4.175	4.664
n_{DC} (%)	55.4	24.9	27.5

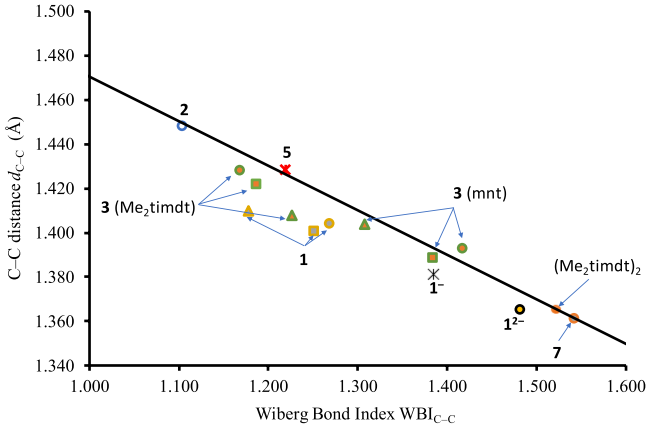

Figure 3. Correlation between optimized C−C bond distances (d_{C-C}) and Wiberg bond indices (WBI_{C-C}) within the 1,2-dithiolene ligand calculated for selected systems (circle, singlet; star, doublet; triangle, triplet; square, singlet diradical).

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Inorg. Chem. 2020, 59, 17385−17401

represent a reliable parameter for evaluating the charge distribution and hence the oxidation state of noninnocent 1,2-dithiolene ligands. When 1,2-dithiolene complexes $\mathbf{1}^{q-}$ (q = 0, 1, 2) are considered, the d_{C-C} and WBI_{C-C} data, while not exactly fitting the correlation, point out that complex $\mathbf{1}^{2-}$ falls in the area of C=C double bonds, very close to $(Me_2timdt)_2$ and compound **7**, therefore confirming the 2-thioxoimidazoline-4,5-dithiolate nature of the ligands in the dianionic complex. Complexes **1** (whatever the approach adopted for describing its GS) and $\mathbf{1}^{-}$ fall in the central area of the graph, indicating an intermediate character of the C−C bond between a single and a double bond.

An examination of the frontier KS-MOs composition shows that, according to the CS description of the GS of **1**, the KS-HOMO and the KS-LUMO are π-MOs represented by the b_{3u} in-phase and b_{2g} out-of-phase combinations of the singly occupied molecular orbitals (SOMOs) of the two $Me_2timdt^{\bullet-}$ ligands (Figure 4a and Figure S8). In fact, the b_{3u} KS-HOMO

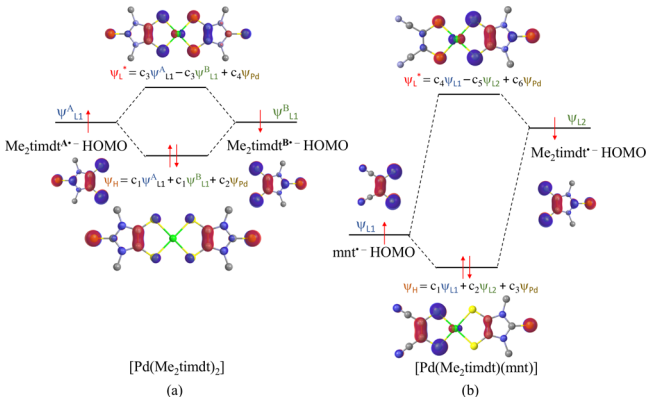

Figure 4. Qualitative MO diagram showing the contributions of the HOMOs of the 1,2-dithiolene ligands to the HOMO and LUMO of complex **1** (a; c_1 48%, c_2 4%; c_3 47.5%, c_4 5%) and complex **3** (b; c_1 61%, c_2 31%, c_3 8%; c_4 24%, c_5 70%, c_6 6%) in the CS GS description. In the KS-MO drawings hydrogens have been omitted for clarity. Cutoff value: 0.05 |e|.

(MO 107 according to a progressive labeling based on an energy scale) is mainly made up of the four $3p_x$ AOs of the four donor S atoms, perpendicular to the molecular yz plane, and the four C $2p_x$ AOs taken with opposite phases. The terminal S atoms also participate in this MO, while the contribution from the central Pd ion is very poor (4%). The 108 b_{2g} KS-LUMO involves the same atomic species as the HOMO with a larger contribution from the bonding sulfur atoms, but the contributions from the two ligands are opposite in phase. In the KS-LUMO, the metal ion is only marginally involved (5%) as well through its $3d_{yz}$ AOs. In the singlet diradical DFT-BS GS configuration, the α- and β-HOMOs show the same composition as the HOMOs of the constituent 1,2-dithiolene $Me_2timdt^{\bullet-}$ ligands, analogously to what was previously reported for different Ni and Pt bis(1,2-dithiolene) metal complexes,[52] the central Pd ion participating to both α and β MOs (3%). Notably, the DFT-BS approach results in a stabilization of the KS-HOMO and destabilization of the KS-LUMO with respect to the restricted CS solution, thus increasing the ΔE_{H-L} gap (Figure 5, top). The CS description of complex **1** features a single allowed NIR one-electron excitation calculated at the TD-DFT level. This corresponds to the $^1A_g \rightarrow {}^1B_{1u}$ transition, involving almost exclusively (97%)

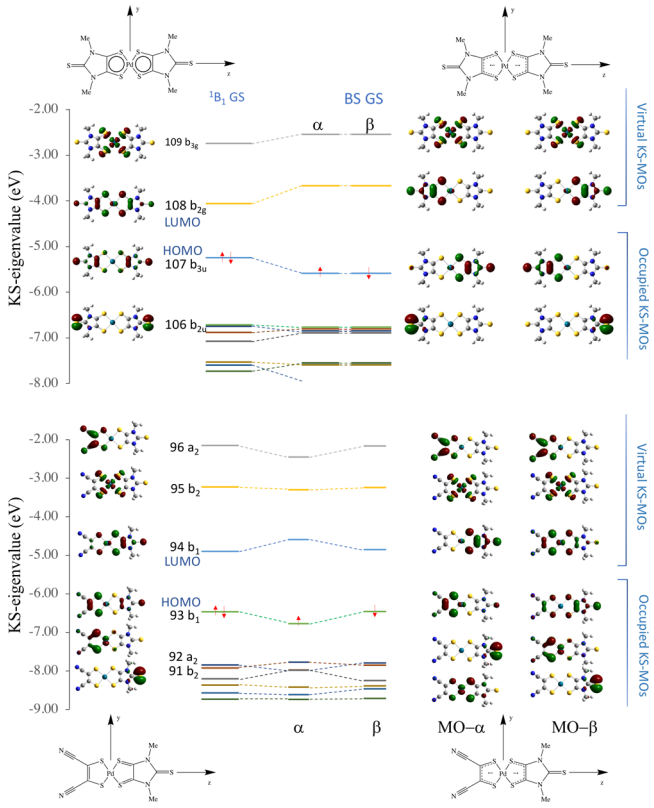

Figure 5. Frontier KS-MO energy diagram (−2 to −8 eV) showing the energy and MO drawing in the restricted (CS GS, left) and singlet diradical (BS GS, right) descriptions for **1** (top) and **3** (bottom). Cutoff value: 0.05 |e|.

the one-electron HOMO−LUMO (H → L) excitation. This is calculated to fall at 963.0 nm (oscillator strength f = 0.436) in the gas phase and 1068.3 nm (f = 0.581) in CH_2Cl_2. The oscillator strength calculated at the TD-DFT level along with the experimental FWHM value of the NIR band were used to evaluate the molar extinction coefficient ε for **1** (eq 6).[101] The symmetric and antisymmetric combinations of the α-107 → α-108 and β-107 → β-108 excitations (H,H → L,L double exciton states) are calculated as BS-GS → ES 1 and BS-GS → ES 2 transitions. Double exciton states have been reported for conjugated chromophores with open-shell diradical character,[127] such as polyenes[138,139] and quinoidal oligothiophenes.[140] The double exciton state is one-photon forbidden, and it has been observed as a weak band at lower energies in comparison to the main absorption band due to the one-photon allowed single exciton state.[127] The symmetry-allowed transition BS-GS → ES 2 falls at wavelength values lower (E = 1.487 eV, λ_{max} = 833.6 nm, f = 0.310) than those predicted for the singlet GS (see above). The complex envelope of the NIR absorption band of neutral [M(R,R′timdt)$_2$] bis(1,2-dithiolene) complexes can be attributed to the contribution of doubly excited states to the main single exciton states, thus possibly accounting for the unusually high molar extinction coefficients observed for the NIR absorption in this class of bis(1,2-dithiolene) complexes.[46,49] The forbidden BS-GS → ES 1 transition (1.142 eV, λ_{max} = 1085.6 nm) may provide a low-energy weak contribution[138] to the NIR absorption due to the vibronic coupling with the B_{1u} antisymmetric combination of the stretching Pd−S vibrations, calculated at 294.1 and 293.2 cm^{-1} at the RDFT and DFT-BS levels, respectively.

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Electronic Structure of [Pd(Me$_2$timdt)(mnt)] (3). The GS geometry for **3** (E_{Abs}^{298K} = 3.784 and 4.872 eV in the gas phase and CH_2Cl_2, respectively) was optimized in its singlet CS ($^1B_1$), triplet open shell ($^3B_1$), and singlet diradical (BS) configurations. The triplet−singlet energy gap classifies **3** as a diradicaloid (Table 4).[91,128] While the $^3B_1$ state is sensibly less stable than the singlet state, the singlet diradical BS ($\langle S^2\rangle_{BS}$ = 0.436) and the $^1B_1$ CS singlet configurations differ by less than 1 kcal mol^{-1} (Table 4). The singlet configurations calculated at the RDFT and DFT-BS levels show very close optimized Pd−S, C−C, and C−S bond distances, only very slightly overestimated (by less than 0.03 Å) in comparison to the relevant structural distances (Table 3). The difference Δd_{C-C} between the C−C bond distances d_{C-C} of the two 1,2-dithiolene ligands (corresponding to the C(1)−C(1)^i and C(4)−C(4)^i structural bond lengths in Figure 1 for the Me$_2$timdt and mnt ligands, respectively) is evaluated correctly (C(1)−C(1)^i > C(4)−C(4)^i), but it is slightly underestimated, so that the calculated dithione-dithiolato character is less pronounced than expected on the basis of the structural data (Table 3). The DFT-BS description of the GS provides a lower Δd_{C-C} value in comparison to the CS description. Accordingly, while the charge Q_{Pd} on the central Pd ion in the CS and in the singlet diradical GSs is essentially unchanged (ΔQ_{Pd} = 0.024 |el), the difference in the charges calculated on the two 1,2-dithiolene ligands at the NBO level is sensibly larger in the former (0.514 and 0.390 |el, respectively). In the RDFT approach, the optimized values for the C−C distances of the Me$_2$timdt and mnt ligands correspond to noticeably different WBIs (1.168 and 1.417 in the $^1B_1$ CS GS) and clearly fall in different regions of the d_{C-C} vs WBI_{C-C} correlation (Figure 3). Therefore, a comparison between structural and DFT-optimized data indicates that the CS description is more suitable than the singlet diradical description in modeling the GS of the mixed-ligand complex **3**. Notably, the value of the C−C bond lengths within the mnt ligand in **3** (1.393 Å, Table 3) is even shorter than the value calculated for the free mnt^{2-} ligand (1.406 Å, Table 2). On passing from **3** to the radical anion **3**$^{\bullet-}$ and the dianion **3**$^{2-}$, only minor differences (lower than 0.02 Å) are observed on the mnt ligand, while the Me$_2$timdt ligand is more greatly affected, the d_{C-C} distance being progressively shortened (d_{C-C} = 1.428, 1.397, and 1.364 Å within the Me$_2$timdt ligand for **3**, **3**$^-$, and **3**$^{2-}$, respectively; Table 3). In summary, a comparison between calculated and experimental data supports the hypothesis that the GS of **3** can be better described as a dithione-dithiolato [Pd^{II}(Me$_2$timdt)(mnt^{2-})] complex with a minor contribution from the singlet diradical [Pd^{II}(Me$_2$timdt$^{\bullet-}$)(mnt$^{\bullet-}$)] description. Accordingly, the diradical character n_{DC} = 24.9% (eq 5) is calculated for complex **3** (Table 4).[141] The KS-HOMO and KS-LUMO in the CS description (MOs 93 and 94, respectively) are π-in-nature MOs mainly located on the mnt (61%) and Me$_2$timdt (70%) ligands, respectively, with only minor contributions from the 4d$_{xz}$ AO of the Pd central atom (6% and 8%, respectively; Table S7). Hence, KS-HOMO and KS-LUMO in the heteroleptic complex can be considered as being derived from the in-phase and out-of-phase combinations of the SOMOs of the constituent ligands mnt$^{\bullet-}$ and Me$_2$timdt$^{\bullet-}$ (Figure 4b and Figures S7 and S8). The former ("pull" electron-withdrawing ligand, HOMO at lower energy) contributes mostly to the KS-HOMO of **3** and assumes a larger character of 1,2-dithiolate, while the latter ("push" ligand, HOMO at higher energy) contributes mostly to the KS-LUMO of **3** and assumes a larger character of 1,2-dithione, in agreement with the structural data discussed above. In the DFT-BS description, the eigenvalues of the corresponding α- and β-MOs are remarkably unequal, reflecting their different compositions (Figure 5 (bottom) and Figure S9). In particular, the α-MO 93 is located on the mnt ligand (76%; Table S8 and (a) in Figure S9), while the β-MO 93 is less stable and is located largely on the Me$_2$timdt ligand (63%; Table S8 and (c) in Figure S9). Conversely, the α-MO 94 is located almost entirely on the Me$_2$timdt ligand (91%; Table S8 and (b) in Figure S9), while the β-MO 94 shows contributions from both ligands (mnt 54%, Me$_2$timdt 36%; Table S8 and (d) in Figure S9).

Therefore, both the RDFT and DFT-BS approaches agree in attributing an LL′CT character to the lowest energy transition, from the mnt "pull" ligand to the Me$_2$timdt "push" ligand. TD-RDFT calculations show, in excellent agreement with experimental data (Figure 2 and Figure S3 in the Supporting Information), three main spectral regions, namely (i) an overlap of intense transitions in the UV region (λ < 280 nm), (ii) a band in the visible region (300 ≤ λ ≤ 500 nm), and (iii) a single very intense NIR transition (λ > 800 nm). In Figure 6,

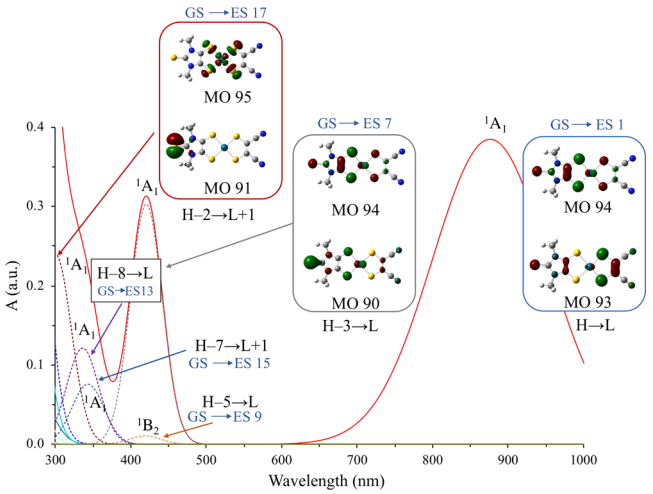

Figure 6. UV−vis−NIR spectrum of **3** simulated on the basis of IEF-PCM TD-RDFT calculations in $CHCl_3$. FWHM w = 90 nm for the $^1A_1$ (H → L) transition, and w = 25 nm for the UV−vis bands. Cutoff value: 0.05 |el.

the UV−vis−NIR spectrum of **3** in $CHCl_3$ solution, simulated on the basis of singlet IEF-PCM TD-RDFT calculations (Table 5), is depicted. The absorption bands in the UV region are due to the overlap of several peaks involving the frontier orbitals, with intraligand (GS → ES 9), interligand (GS → ES 13), or ligand-to-metal (GS → ES 15 and GS → ES 17) character. The absorption in the visible region is mainly due to the GS → ES 7 intraligand transition, involving mainly the KS-HOMO-3 and KS-LUMO, centered on the Me$_2$timdt ligand and the Pd^{II} ion. A single intense transition is calculated in the NIR region, falling at 1.489 eV (Table 5). This transition involves almost exclusively (88.4%) the one-electron excitation from the KS-HOMO (MO 93) to the KS-LUMO (MO 94). Notably, the oscillator strength f calculated for the NIR transition (0.315) is sensibly lower than that calculated for **1** (f = 0.436, see above), in agreement with the experimental values determined for the corresponding molar extinction coefficients. TD-RDFT calculations were carried out at the IEF-PCM level

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Inorg. Chem. 2020, 59, 17385−17401

Table 5. Energies E (eV), Wavelengths λ (nm), and Oscillator Strengths f of the Main ($f \geq 0.005$) UV−vis−NIR Electronic Transitions Calculated for 3 in the Gas Phase and in CH_2Cl_2 and $CHCl_3$ at the IEF-PCM TD-RDFT Level[a]

		gas phase			$CHCl_3$			CH_2Cl_2			
ES[b]	symm	E	λ	f	E	λ	f	E	λ	f	main contribution
1	$^1A_1$	1.489	832.6	0.315	1.415	876.0	0.385	1.436	863.8	0.368	H(93) → L(94) (100%)
7	$^1A_1$	2.931	423.0	0.153	2.950	420.3	0.303	2.974	416.9	0.324	H-3(90) → L(94) (91%)
9	$^1B_2$	2.983	415.7	0.009	2.962	418.6	0.011	2.966	418.0	0.008	H-5(88) → L(94) (92%)
13	$^1A_1$	3.586	345.8	0.096	3.691	335.9	0.121	3.719	333.4	0.122	H-8(85) → L(94) (91%)
15	$^1B_2$	3.787	327.4	0.046	3.616	342.9	0.076	3.583	346.1	0.076	H-7(86) → L+1(95 (15%), H(93) → L+2(96) (75%)
17	$^1A_1$	4.133	300.1	0.121	4.135	299.9	0.240	4.132	300.1	0.250	H-2(91) → L+1(95) (96%)
20	$^1B_2$	4.364	284.2	0.005	4.294	288.8	0.007	4.274	290.1	0.006	H-13(80) → L+1(95) (19%), H-9(84) → L+1(95) (65%)

[a]KS-HOMO (H) = MO 93; KS-LUMO (L) = MO 94. [b]Excited state (ES) numbering taken from gas-phase calculations.

of theory in the same solvent systems experimentally adopted to record UV−vis−NIR spectra. The calculated NIR transition energies are generally overestimated but are linearly correlated to the experimental energies (R^2 = 0.88; E_{calc} (eV) = 0.374; E_{exp} + 0.979; Table 1 and Figure S10). Both in the gas phase and in the solvents considered at the IEF-PCM level, the NIR transition is attributed exclusively to the H → L one-electron excitation. Accordingly, a linear correlation holds between the calculated transition energies in the NIR region and the ΔE_{H-L} energy gap evaluated in each of the examined solvents (Table 1; R^2 = 0.92). Along the series $CHCl_3$, CH_2Cl_2, THF, CH_3CN, and DMF the contribution of the mnt fragment to KS-HOMO and KS-LUMO slightly increases (68% to 70%) and decreases (16% to 13%), respectively (Table S7). The contribution of the Me_2timdt fragment to the KS-HOMO and to the KS-LUMO decreases (23% to 20%) and increases (78% to 82%), respectively. Therefore, on passing to $CHCl_3$ to DMF, the NIR transition assumes a larger LL′CT character, and the ΔE_{H-L} energy gap increases from 1.68 eV in $CHCl_3$ to 1.77 eV in DMF and CH_3CN, in agreement with the experimental trend of NIR absorption energies (Table 1). Calculated oscillator strengths f fall between 0.356 and 0.385 in DMF and $CHCl_3$, respectively (Table S9). Oscillator strength values calculated at the TD-DFT level have been used along with experimental full widths at half-maximum (FWHM, w) to evaluate the ratio between the extinction coefficient in each solvent and that in $CHCl_3$ solution. The resulting scaled calculated extinction coefficients $\varepsilon_{calc}^{corr}$ (Table 1) progressively decrease with an increase in the transition energies. TD-DFT calculations were carried out on **3** in the singlet diradical electron configuration. Since the two α-93 → α-94 and β-93 → β-94 (H → L) excitations are not degenerate (Figure 5, bottom), the α-excitation contributes mainly (58.1%) to the symmetry-allowed transition at higher energy (0.853(α-93 → α-94) − 0.464(β-93 → β-94); E = 1.629 eV, λ = 761 nm, f = 0.267 in the gas phase), while the β-excitation contributes to the transition at lower energy (0.486(α-93 → α-94) + 0.881(β-93 → β-94); E = 0.746 eV, λ = 1663 nm, f = 0.033), forbidden in the C_{2v} point group. Although the contribution of the singlet diradical description to the GS of **3** is limited, it is conceivable that the former transition, corresponding to a double exciton state, can provide a high-energy component to the NIR transition. Notably, due to its nature, the double exciton transition is predicted to show remarkable solvatochromic effects, thus accounting for the different spectral shapes observed on varying the solvent (Table 1 and Figure S6).

Finally, the lack of an inversion center in the title complexes suggests a possible application of heteroleptic bis(1,2-dithiolene) complexes as second-order nonlinear optical (SONLO) materials. Prompted by the results obtained at TD-DFT level, since small geometrical differences can determine large differences in NLO properties,[38,39] we calculated static dipole moments (μ) and static first (quadratic) hyperpolarizabilities (β_{tot}) for **3** in the gas phase and in CH_2Cl_2 and $CHCl_3$ solutions (Table S10).[109] Calculations were also carried out at the DFT-BS level (Table S10) in the gas phase. For the sake of comparison, the same calculations were also undertaken, at the same level of theory, on [Pt(phen)(tdt)] (phen = 1,10-phenanthroline; tdt^{2-} = 3,4-toluenedithiolate; Chart S2), a neutral diimine-dithiolate Pt complex showing a very large hyperpolarizability value among those investigated experimentally by means of EFISH measurements (λ_{max} = 583 nm; $\beta_\mu = -28 \times 10^{-30}$ esu with $\omega = 1.569 \times 10^{11}$ GHz; zero-frequency $\beta_0 = -16 \times 10^{-30}$ esu).[71] In agreement with the charge distribution within complex **3**, the μ vector lies along the molecular z axis and β shows only tensor z components. As previously observed for different heteroleptic metal complexes containing 1,2-dithiolato ligands,[62] a dramatic increase in β_{tot} was calculated when solvation is taken into account ($|\beta_{tot}| = 37.6 \times 10^{-30}$, 475.6×10^{-30}, and 330.5×10^{-30} esu in the gas phase, CH_2Cl_2, and $CHCl_3$, respectively). In addition, when the diradical character of **3** is evaluated at the DFT-BS level, the β_{tot} value dramatically increases (177.4×10^{-30} esu in the gas phase), reaching the same order of magnitude computed for [Pt(phen)(tdt)].

CONCLUSIONS

DFT calculations have been exploited to investigate the structural and spectroscopic features of the heteroleptic mixed-ligand neutral complex Pd^{II} bis(1,2-dithiolene) **3**, to highlight the differences between the homoleptic related complexes **1** and **4** and to develop sound structure−property relationships. The closed-shell (CS) description is only partially suitable to describe the electronic structure of bis(1,2-dithiolene) complexes, and—whatever the nature of the ligands—the singlet diradical character (DC) must be taken into account. The broken-symmetry (BS) approach within DFT, although itself a dramatic approximation underestimating the DC of bis(1,2-dithiolene) metal complexes, is a useful tool in supplementing the description of the ground state (GS). A few general conclusions can be drawn

(1) The nature of the 1,2-dithiolene ligand is responsible for the relevance of diradical character (DC) in the GS of 1,2-dithiolene complexes. In homoleptic neutral bis(1,2-dithiolene) complexes, on passing from complex **4** to complex **1**, the n_{DC} index is roughly doubled. This can

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be related to the capability of the ligands $mnt^{\bullet-}$ and $Me_2timdt^{\bullet-}$, respectively, to stabilize the unpaired electron. In heteroleptic mixed-ligand complexes, the absolute one-electron-reduction potentials E_{Abs}^{298K} calculated for the $\mathbf{L}/\mathbf{L}^{\bullet-}$ and $\mathbf{L}'/\mathbf{L}'^{\bullet-}$ couples can be used to evaluate the nature of the $[Pd^{II}(\mathbf{L})(\mathbf{L}')]$ complex. The 1,2-dithiolene ligand displaying the largest reduction potential ("pull" ligand) features its π-NBMO at lower energy and contributes largely to the KS-HOMO of the heteroleptic complex, while that with the lowest potential ("pull" ligand) contributes to the KS-LUMO. As a consequence, it is conceivable that the difference ΔE_{Abs}^{298K} in the absolute reduction potentials of the ligands **L** and **L′** can be adopted as a useful parameter to estimate the push−pull nature of the resulting heteroleptic neutral complexes $[Pd^{II}(\mathbf{L})(\mathbf{L}')]$ and the different localizations of the KS-HOMO and KS-LUMO. A larger push−pull character points to a larger dithione-dithiolato nature and a lower DC of the complex. This implies that the DC is the largest in homoleptic bis(1,2-dithiolene) complexes $[Pd^{II}(\mathbf{L})_2]$ with ligands **L** featuring low values of E_{Abs}^{298K}, such as Me_2timdt, and decreases in heteroleptic complexes $[Pd^{II}(\mathbf{L})(\mathbf{L}')]$ in dependence on ΔE_{Abs}^{298K}.

(2) Several authors have observed that metal−sulfur bond lengths optimized at the DFT level are slightly overestimated in comparison to structural bond distances. This can be attributed to the use of RDFT calculations in complexes featuring a significant DC. The DFT-BS approach leads to bond distances closer to the structural distances. It can be deduced that, in the case of complexes with a large DC, such as complex **1**, the difference between CS-optimized distances and the relevant experimental metric parameters increases with the DC of the complex.

(3) The spectral shape of the NIR band of neutral bis(1,2-dithiolene) metal complexes has been indicated to be a complex envelope resulting from a series of d−d transitions with different spin couplings to the open-shell ligands. The intensity of this band, peculiar to metal bis(1,2-dithiolene) complexes, may be attributed not only to the very large oscillator strength f calculated for the HOMO−LUMO one-electron excitation within a CS description but also to the contribution of double exciton states typical of diradical species. To a lower extent, double exciton states are possible also in heteroleptic bis(1,2-dithiolene) complexes and can be related to the spectral shapes observed for the NIR band in different solvents.

(4) The intrinsic optical nonlinearity of heteroleptic bis(1,2-dithiolene) complexes is enhanced by their DC, providing a further criterion, in addition to the lack of an inversion center and large electric dipole moment values, for the rational design of NLO materials active in the vis−NIR region.

Summarily, this investigation shows that the DC of bis(1,2-dithiolene) metal complexes can be extensively modulated by means of the choice of the substituents R at the 1,2-dithiolene core, allowing for the rational design of the linear and nonlinear optical properties of the resulting complexes and hence the possibility of applying them in fields as varied as nonlinear optics, photoconductivity, and electrochromism.

Further studies are ongoing in our laboratory to investigate in detail the role of the central metal ion and to generalize the limited findings described here for the Pd^{II} complexes with the mnt and Me_2timdt ligands to other homoleptic and heteroleptic bis(1,2-dithiolene) complexes differing in the nature of the central metal ions and 1,2-dithiolene ligands.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.inorgchem.0c02696.

Details on theoretical calculations, molecular schemes for the compound discussed in the paper, crystallographic data and packing details for complex **3**, experimental UV−vis−NIR spectra decomposed into their component Gaussian peaks, NIR spectra in MeCN, DMF, THF, CH_2Cl_2, and $CHCl_3$, KS frontier MO drawings calculated for Me_2timdt^{q-}, mnt^{q-} (q = 0, 1, 2), and complex **3**, RDFT, DFT-BS, and (IEF-PCM) TD-DFT data for **1** and **3**, and calculated second-order hyperpolarizabilities β and dipole moments μ (PDF)

Accession Codes

CCDC 2027023 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Inorg. Chem. 2020, 59, 17385−17401

Author Contributions

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Notes

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■ ABBREVIATIONS

BS, broken symmetry; CS, closed shell; DC, diradical character; GS, ground state; MO, molecular orbital; HOMO, highest occupied molecular orbital; KS, Kohn−Sham; LUMO, lowest unoccupied molecular orbital; NBMO, nonbonding molecular orbital; NLO, nonlinear optics; SONLO, second-order nonlinear optics.

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Inorg. Chem. 2020, 59, 17385−17401