Bipyridyl– and pyridylquinolyl–phenothiazine structures as potential photoactive ligands: Syntheses and complexation to palladium

Alexis Tabey, Jonathan Mendy, Philippe Hermange *, Eric Fouquet *

Univ. Bordeaux, Institut des Sciences Moléculaires, UMR-CNRS 5255, 351, Cours de la Libération, 33405 Talence Cedex, France

ABSTRACT

Three new bipyridyl– and pyridylquinolyl–phenothiazine structures were synthesized through Pd-catalyzed C–N couplings between phenothiazine and the corresponding bromo-heteroaryls. For the 2-(*N*-phenothiazine)-bipyridine, boat conformation was determined for the phenothiazine moiety by X-ray diffraction analysis. Single well-defined palladium acetate complexes were observed by ^{1}H NMR analysis with the 4-(*N*-phenothiazine)-bipyridine and the pyridyl-5-(*N*-phenothiazine)-quinoline. Compared to the naked ligands, the UV–visible absorption spectra showed, in these cases, significantly red shifted λ_{max} upon coordination. Preliminary modeling experiments with the free and the coordinated 4-(*N*-phenothiazine)-bipyridine suggested for both the occurrence of electronic transfers from the phenothiazine to the bipyridine. Potentially enabling the tuning of the electron density of the coordinating moiety upon near-UV irradiation, this bipyridyl–phenothiazine structure could be the origin of a novel class of photo-active ligands for applications in organometallic catalysis.

Tremendous attention has been recently focused on the development of novel efficient, mild and green synthetic methods using visible-light photoredox catalysis, and the field is now well-established as a powerful strategy in the toolbox of organic chemists.[1] Indeed, excited states of metal- or organic-based photosensitizers (PS) are generally suitable for single electron transfers (SET) with a wide range of substrates. As a result, photoredox catalysis facilitates the access to highly reactive radicals, prone to consecutive chemical transformations,[2] or can be combined to other organic- or organometallic-catalytic cycles, increasing exponentially the synthetic possibilities.[3] For instance, previously inaccessible elementary steps can be achieved by *in situ* modification of the oxidation state of an organometallic intermediate, through SET between the photo-excited PS* and the metallic center.[4] In all cases, concomitantly with oxidation and reduction potentials, lifetime of the photo-excited species is an essential parameter in these *inter-molecular* electron transfers, and can sometimes be a restrictive point in the development of new synthetic methods.[5] Thus, *intramolecular* processes would allow to suppress this constraint, and could improve the overall efficiency of the reaction. For example, the design of novel unimolecular photosensitizer – catalyst structures has already proved to be a successful strategy for double

bond isomerisation,[6] thioether oxidation[7] or C–C bond formation.[8] Ru(bpy)$_x$ and Ir(bpy)$_x$-derivatives were used in most of these studies for their ideal photo-physical properties.[1b] However, organic-based moieties also showed promising properties,[9] avoiding the using of costly metals. In this context, we aimed to design new bipyridyl-based ligands directly coupled to a full-organic photo-sensitive unit. Indeed, after complexation to the metal catalyst, internal electronic transfers might occur under irradiation, which could tune finely the catalytic synthetic activity of the complex.[10,11] Applied in numerous field like solar cells,[12] sensors,[13] atom transfer radical polymerization (ATRP),[14,15] or photoredox catalysis,[16] the phenothiazine moiety (PTZ) was selected as light absorbing entity and its Pd-catalyzed C–N coupling[17] was envisaged with bromo-substituted bipyridyl or pyridylquinolyl backbones (Scheme 1).

Commercial 6-bromo-2,2-bipyridine **1** was firstly selected as substrate and reacted with phenothiazine employing Pd(dba)$_2$ (2 mol%) as palladium source, HP^{t}Bu$_3$. BF$_4$ (10 mol%) as ligand and ^{t}BuOK (1.5 equiv.) as base in toluene at 80 °C for 24 h.[18] However, only traces of products could be detected in this case. Thus, keeping ^{t}BuOK (1.5 equiv.) as base, RuPhos-Pd-G2 was selected as precatalyst (10 mol%) and the reaction was run in dioxane at 110 °C for 18 h.[14] With this new set of conditions, the desired product was secured in a correct yield of 48% after column chromatography on silica gel (Fig. 1, A). Interestingly, slow evaporation of a CDCl$_3$ solution of **L1** allowed to produce suitable monocrystals
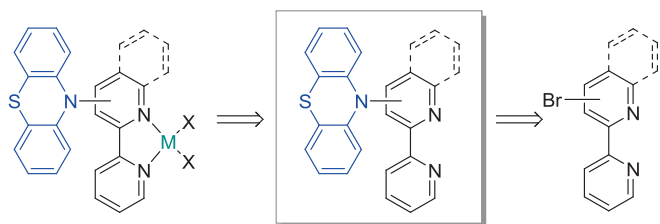
Scheme 1. Retro-synthetic route envisaged for the preparation of the bipyridyl– and pyridylquinolyl–phenothiazine ligands.
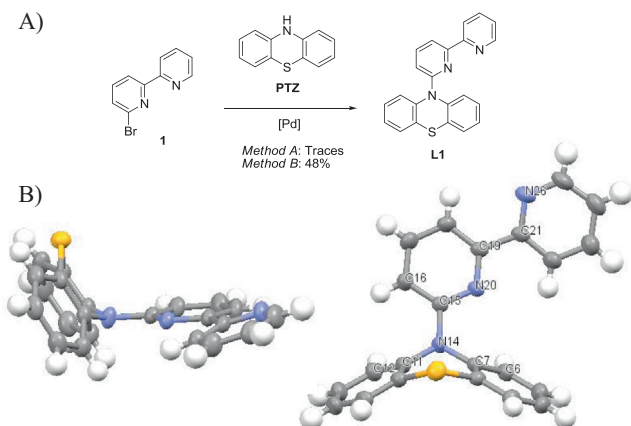

Fig. 1. Synthesis of ligand **L1** and Mercury drawings of its structure obtained by X-ray diffraction analysis. (A) Method A: 6-bromo-2,2-bipyridine (0.65 mmol), phenothiazine (1.1 equiv), Pd(dba)$_2$ (2 mol%), HP^{t}Bu$_3$. BF$_4$ (10 mol%), t-BuOK (1.5 equiv), toluene (1 mL) at 80 °C for 24 h. Method B: 6-bromo-2,2-bipyridine (0.3 mmol), phenothiazine (1.3 equiv), RuPhos-Pd-G2 (10 mol%), t-BuOK (1.5 equiv), dioxane (1 mL) at 110 °C for 18 h. (B) Drawings with 50% thermal ellipsoids. Selected torsion angles: (C7)–(N14)–(C15)–(N20) 15.65°, (C11)–(N14)–(C15)–(C16) −7.22°, (C15)–(N14)–(C11)–(C12) 71.84°, (C15)–(N14)–(C7)–(C6) −72.59°, (N20)–(C19)–(C21)–(N26) −166.32°.

for X-ray diffraction analysis (Fig. 1, B).[19] The expected boat conformation of the phenothiazine was confirmed by this solid-state structure, and bond lengths/angles were similar to previously described values for N-heteroaryl-phenothiazine.[20] Especially, the torsion angles measured at the PTZ nitrogen indicated a more important lone pair delocalization into the 2,2′-bipyridyl functionality than into the two *ortho*-phenylene groups of the phenothiazine.

Then, the same synthetic procedure was applied to two other bromo-heteroaryls. Firstly, 4-bromo-2,2-bipyridine **2** was prepared according to the literature[21] and reacted with phenothiazine to obtained the desired coupling product **L2** with an excellent yield of 93% (Scheme 2). Then, the 5-bromoquinoline derivative **3** was synthesized by a Friedländer condensation between 2-amino-6-bromobenzaldehyde **4** and 2-acetylpyridine **5**.[22] Quinoline **3** was isolated in an excellent yield of 92% and engaged in the following C–N bond formation step to obtain ligand **L3** in 56% yield.[23]

Sulfur is known to be an excellent coordinating atom for metals, and adding a phenothiazine group might disturb the desired bidentate ligation expected from the bipyridyl moiety. As palladium has already demonstrated interesting synthetic applications when combined to photo- and redox-active ligands,[8,24] we decided to evaluate this potential issue by studying the complexation of our set of molecules to Pd(II). **L1**, **L2**, **L3** and the reference compound 2,2′-bipyridine (bpy) were mixed with equimolar quantities of Pd(OAc)$_2$ in deuterated chloroform, and sonicated for 60 min before recording the ^{1}H NMR spectra of the resulting solutions (Fig. 2).[25] A mixture of two species in a 40:60 ratio was observed in the case of **L1**, probably due to the presence of rotamers or to the various
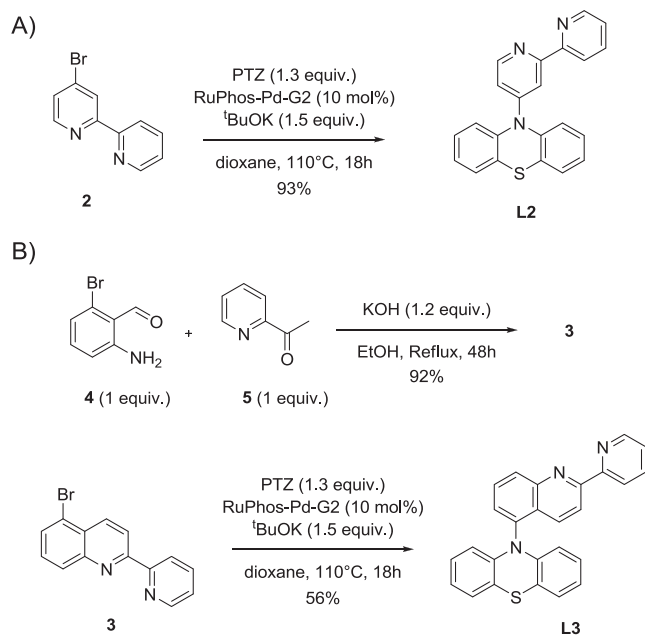
Scheme 2. Syntheses of ligands **L2** and **L3**.

bidentate complexation possibilities for the palladium in this potential tri-or tetra-dentate ligand. On the contrary, single well-defined species were observed for both ligands **L2** and **L3**.

The ^{1}H NMR spectra of the **L2** - palladium acetate complex (1:1) was very similar to (bpy)Pd(OAc)$_2$, supporting common structural parameters for the two species.[26] Upon complexation, both led to deshielded signals of 4′ and shielding of the 6,6′/3,3′ protons. Interestingly, all the signals of the protons of the phenothiazine group were also shifted downfield (up to 0.1 ppm), which indicated a decrease of the electron density in this moiety. The same tendency was observed for **L3**, with a deshielding of the PTZ signals ranging from 0.02 to 0.08 ppm. However, in this case, the overall electron density remains higher in this part of the molecule when compared to (**L2**)Pd(OAc)$_2$. This was consistent with the more important delocalization of the lone pair of the PTZ nitrogen into the two *ortho*-phenylene groups, which can be observed with more hindered N-heteroaryl-phenothiazine.[27]

Having demonstrated the coordinating abilities of the **L2** and **L3** ligands, the potential behavior upon photoexcitation of the resulting complexes with palladium acetate were examined. After switching the solvent to acetonitrile,[28] UV–visible absorption of these species were measured and compared to the free ligands, as summarized in Fig. 3.

In both cases, the number of local extrema between 300 and 500 nm was identical for the free and the coordinated ligands. For example, one absorption band at 314 nm was observed for **L2**, which could be assigned to a π-π* transition,[29] and this λ$_{max}$ was red shifted to 354 nm upon complexation, indicating a strong decrease of the energy gap of this electronic transition. Similarly, a bathochromic effect appeared when forming (**L3**)Pd(OAc)$_2$. Indeed, the 322 nm and 337 nm peaks of **L3** were shifted to 343 nm and 358 nm, respectively. It should be noted that no specific transition could be detected for (bpy)Pd(OAc)$_2$ in this range of wavelengths, proving the benefits of the PTZ moiety when employing near-ultraviolet or visible light irradiations.

Attempting to understand these effects, simple preliminary modeling experiments were realized to compare the HOMO and LUMO in **L2** and (**L2**)Pd(OAc)$_2$ (Fig. 4).[30] For the naked ligand, the highest occupied molecular orbital was mainly centered onto the phenothiazine, whereas its lowest unoccupied molecular orbital