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## Unexpected formation of a $\mu$ -carbido diruthenium(IV) complex during the metalation of phthalocyanine with $\text{Ru}_3(\text{CO})_{12}$ and its catalytic activity in carbene transfer reactions†

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A  $\mu$ -carbido diruthenium(IV) phthalocyanine complex was prepared for the first time from the free-base octabutoxyphthalocyanine by direct metalation with  $\text{Ru}_3(\text{CO})_{12}$ . The first examples of the catalytic activity of Ru(IV) binuclear phthalocyanines were demonstrated by the cyclopropanation of aromatic olefins and carbene insertion into the N–H bonds of aromatic or aliphatic amines with turnover numbers of 680–1000 and 580–1000, respectively.

Ruthenium complexes with tetrapyrrolic ligands can be considered as close analogues of iron porphyrins which constitute active sites of hemoproteins playing crucial roles in the transfer of small molecules and oxidation of organic substrates in Nature. To date, ruthenium porphyrins have already found wide catalytic applications in various synthetic procedures,<sup>1</sup> including oxidation,<sup>2</sup> nitrene and carbene transfer reactions,<sup>3</sup> amination<sup>4</sup> and other reactions.<sup>5</sup> Myoglobin modified through iron cofactor substitution with ruthenium porphyrin showed moderate activity for carbene insertion reactions.<sup>6</sup> By contrast, catalytic applications of related ruthenium(II) phthalocyanine analogues are limited by few examples of oxidation<sup>7</sup> and cyclopropanation reactions.<sup>8</sup> At the same time, due to robust chemical properties of phthalocyanine macrocycles, their ruthenium complexes might also give rise to novel catalytic systems.

Herein we report on the unexpected synthesis and catalytic activity of the  $\mu$ -carbido diruthenium(IV) phthalocyanine

complex in the cyclopropanation of styrenes and in the carbene insertion into the N–H bonds of anilines using ethyl diazoacetate (EDA) as a carbene donor.

Ruthenium phthalocyaninates are typically prepared by the template condensation of phthalonitriles in the presence of ruthenium salts or complexes.<sup>9</sup> Direct insertion of ruthenium into the preformed macrocycle is, however, less studied and it is used mainly for the metalation of alkyl-substituted phthalocyanines with  $\text{Ru}_3(\text{CO})_{12}$  in refluxing benzonitrile, affording complexes with two axially coordinated PhCN molecules.<sup>10</sup> Our attempt to apply this method to octa-*n*-butoxyphthalocyanine  $\text{H}_2[(\text{BuO})_8\text{Pc}]$  failed.

Nevertheless, the reaction of  $\text{H}_2[(\text{BuO})_8\text{Pc}]$  with  $\text{Ru}_3(\text{CO})_{12}$  (Scheme 1) smoothly proceeds in refluxing *o*-dichlorobenzene (*o*-DCIB) similarly to the previously published preparation of ruthenium porphyrinates.<sup>11</sup> The separation of the reaction products by size-exclusion chromatography on Bio-Beads S-X1 revealed that two different complexes with essentially different retention times were obtained as a result of the metalation reaction. The structures of complexes were evidenced by UV-Vis, FTIR, MALDI TOF MS and NMR techniques (Fig. 1 and ESI†). One of them with the longer retention time, obtained with a 62% yield, corresponded to the monomeric Ru(II) complex with an axially coordinated CO molecule –  $[(\text{BuO})_8\text{Pc}]\text{Ru}(\text{CO})$ , **1**. The complex with the shorter retention time, formed with a 22% yield, had an unusual UV-Vis spectrum with the broad low-intensity Q-band centered at 607 nm (Fig. 1a). A set of spectroscopic data allowed us to assign this complex to the dimeric phthalocyaninato-Ru(IV) complex with a  $\mu$ -carbido bridge  $[(\text{BuO})_8\text{PcRu}]_2(\mu\text{-C})$ , **2**. The HR ESI mass spectrum showed a prominent molecular cluster of a doubly-charged molecular ion centered at  $m/z = 1196.512$  (Fig. S6†). Their position and isotopic pattern corresponded to those in the simulated spectrum of  $\text{C}_{129}\text{H}_{160}\text{N}_{18}\text{O}_{16}\text{Ru}_2$  (calcd  $m/z = 1196.516$ ). In its FTIR spectrum the band of the Ru=C=Ru stretching at  $1013\text{ cm}^{-1}$  was observed whereas the band of the CO stretching ( $1939\text{ cm}^{-1}$  in the spectrum of **1**) was absent (Fig. 1b).<sup>12,13</sup> The sandwich structure of this complex was

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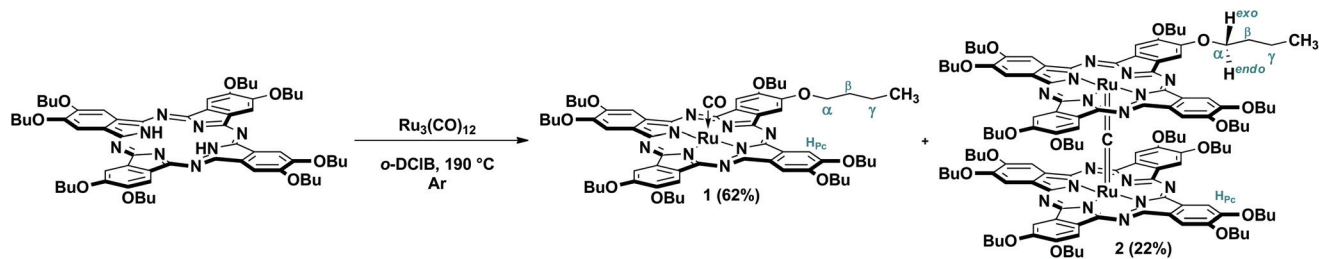
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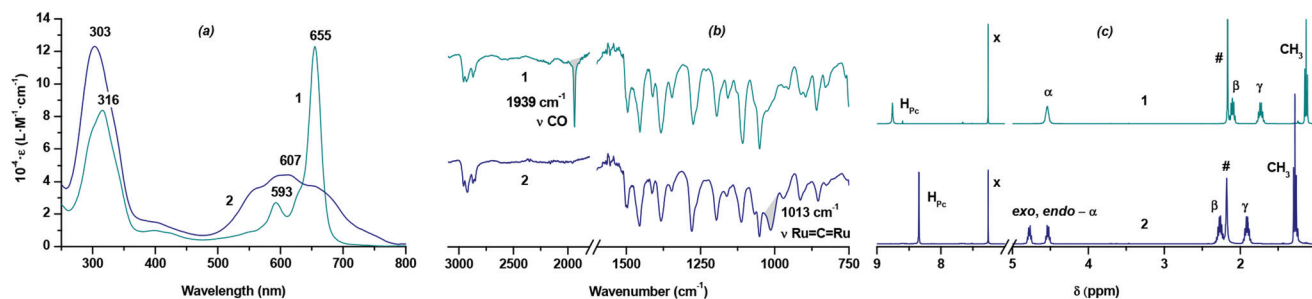
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**Scheme 1** Synthesis of monomeric octabutoxyphthalocyaninoruthenium(II) carbonyl complex **1** and dimeric  $\mu$ -carbido-bis[octabutoxyphthalocyaninoruthenium(IV)] complex **2** with numbering of protons used for the assignment of  $^1\text{H}$  NMR spectra.



**Fig. 1** (a) UV-Vis spectra of complexes **1** and **2** in  $\text{CHCl}_3$ ; (b) FTIR (neat) spectra of complexes **1** and **2**; (c)  $^1\text{H}$  NMR spectra of complexes **1** and **2** in  $\text{CDCl}_3 + 1 \text{ vol}\% \text{ Py-d}_5$ , "x" and "#" mark proton resonance signals of chloroform and water.

further confirmed by the characteristic splitting of the  $\text{O-CH}_2$  resonance signal in the  $^1\text{H}$  NMR spectrum of **2**.

This splitting is due to the non-equivalence of *exo*- and *endo*-protons in this group with respect to the space between the phthalocyanine ligands (Fig. 1c), which was also demonstrated by  $^1\text{H}$ - $^{13}\text{C}$  HSQC NMR spectroscopy (Fig. S11†).<sup>14</sup>

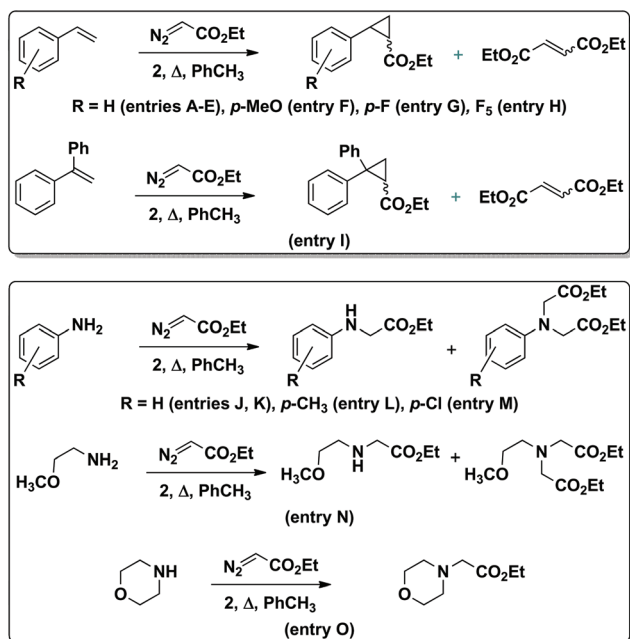
It is known that thermolysis of  $\text{Ru}_3(\text{CO})_{12}$  can lead to carbide clusters; among them the most well-studied one is the octahedral cluster  $\text{Ru}_6\text{C}(\text{CO})_{17}$ , which is formed upon heating of ruthenium carbonyl in high boiling solvents.<sup>15</sup> Therefore, we supposed that complex **2** can be formed either by thermolysis of the carbonyl-containing complex **1**, or *via* the reaction of  $\text{H}_2[(\text{BuO})_8\text{Pc}]$  with  $\text{Ru}_6\text{C}(\text{CO})_{17}$ . However, neither refluxing of the latter reagents in *o*-DCIB nor heating of **1** in the same solvent resulted in the formation of **2**. Therefore, we can propose that complex **2** was formed simultaneously with **1** *via* the reaction of  $\text{H}_2[(\text{BuO})_8\text{Pc}]$  with some intermediate products formed upon the thermolysis of  $\text{Ru}_3(\text{CO})_{12}$ . This tentative mechanism might be corroborated by the results of DFT calculations which suggest that among all the possible products of thermolysis of  $\text{Ru}_3(\text{CO})_{12}$ ,  $\text{Ru}_6\text{C}(\text{CO})_{17}$  has the lowest reactivity, while the other complexes  $\text{Ru}_6\text{C}(\text{CO})_{23-n}$  should be less stable towards further chemical transformations.<sup>16</sup>

Although carbido complexes have been well-known in ruthenium chemistry for a long time,<sup>17</sup> the herein reported  $\mu$ -carbido-dimer **2** is exceptionally rare in the chemistry of ruthenium complexes with tetrapyrrolic ligands. It is limited to the single example of the unsubstituted  $(\text{PcRu})_2(\mu\text{-C})$ , reported by Homborg *et al.* in 1997.<sup>13,18</sup> This complex was synthesized by

the reaction of  $\text{PcRuCl}$  with chloroform as a source of a carbon atom in the presence of KOH in *i*-PrOH and it is poorly soluble in organic solvents, which limits its possible applications. In contrast, the  $\mu$ -carbido complex **2** bearing a substituted ligand formed in an unprecedented one-step procedure starting directly from the phthalocyanine ligand is well-soluble in common solvents which facilitates the investigation of its properties.

Until recently, single-atom bridged bimetallic complexes with porphyrin and phthalocyanine ligands have been regarded as inactive forms in catalysis. However,  $\mu$ -oxo diiron phthalocyanines were shown to be effective catalysts for the oxidation of aromatic compounds to quinones.<sup>19</sup> In turn,  $\mu$ -nitrido diiron phthalocyanine and porphyrin complexes were found to exhibit a rare catalytic activity<sup>20</sup> including oxidation of methane<sup>21</sup> and aromatic compounds,<sup>22</sup> oxidative dechlorination<sup>23</sup> and defluorination<sup>24</sup> as well as the formation of C-C bonds.<sup>25</sup> However, related  $\mu$ -carbido diiron macrocyclic complexes have never been reported as catalysts for any reaction. In this context, it is greatly of interest to explore the possible catalytic applications of the novel  $\mu$ -carbido ruthenium dimer. Thus, the catalytic activity of **2** in the cyclopropanation of styrenes and in the carbene insertion into the N-H bond of anilines using ethyl diazoacetate (EDA) as a carbene donor was investigated (Scheme 2). These reactions provide an access to cyclopropanes or unnatural amino acids and N-heterocyclic compounds, respectively, representing important building blocks used for the synthesis of numerous bioactive molecules.<sup>26</sup>





**Scheme 2** Carbene transfer from EDA to aromatic olefins (top) and amines (bottom), catalyzed by complex 2.

The catalytic activity of **2** (0.1 mol% loading) was initially studied using 1 M styrene solution in toluene and 1.2 equiv. EDA (Table 1). To limit the formation of diethyl maleate and diethyl fumarate byproducts formed from the dimerization of EDA in a ~90:10 ratio, the carbene precursor was slowly added to the reaction mixture. This allowed increasing the yield of ethyl 2-phenylcyclopropane-1-carboxylate from 66% to 84% at 70 °C (Table 1, entries B–D).

The yield of the cyclopropanation product was further improved to 92% at 90 °C (Table 1, entry E). In the absence of catalyst, 4% and 12% styrene conversions were obtained at 70 °C and 90 °C, respectively, thus indicating the involvement of **2** in product formation. The UV-Vis spectrum of the reaction

mixture during the cyclopropanation of styrene in toluene exhibited the same maximum at 618 nm as the spectrum of the initial complex **2** indicating that **2** retained the dimeric structure. Aromatic olefins bearing donor and acceptor substituents were cyclopropanated with 95–100% yields. Even in the case of very electron-deficient pentafluorostyrene, a 68% yield of C<sub>6</sub>F<sub>5</sub>-containing cyclopropane (entry H) has been achieved. The *trans/cis* ratio of the cyclopropanation products was insensitive to the olefin nature: ~70:30 selectivity was observed in all cases. The yield of the cyclopropane product obtained from styrene and EDA in the presence of **2** (92%) was higher than those published for mononuclear Ru(III)PcCl (59%) and Ru(II)PcF<sub>16</sub> (80%) complexes.<sup>8</sup>

The  $\mu$ -carbido diruthenium complex also catalyzes carbene insertion from EDA into the N–H bonds of aromatic and aliphatic amines (Table 2). Importantly, even with low catalyst loading and very high aniline concentration the  $\mu$ -carbido ruthenium complex **2** transfers the carbene group to the amine N–H bonds. It should be noted that many catalytic complexes coordinate with the amine substrates and thus become inactivated to reaction with the carbene precursor.<sup>3,27</sup> To overcome this limitation, a high concentration of catalyst and low amine concentration should be used, which lead to low turnover numbers and low efficiency. Complex **2** doesn't suffer from this and can be used in low concentration to provide a turnover number up to 1000. The insertion of carbenes into the N–H bonds occurs more cleanly than cyclopropanation. Practically no EDA dimerization products were formed. The reaction mediated by **2** was the most efficient at 90 °C. In the absence of the catalyst the conversion of aniline was limited to 5%. The reaction is tolerant of both electron-donating and electron-withdrawing groups on the aromatic moiety. Substituted anilines converted to mono- and di-insertion products with ~80:20 ratios. However, **2** is slightly less efficient in the reaction with aliphatic amines (entries N and O) providing a 58% yield of a double insertion product with 2-methoxyethylamine and a 90% yield with morpholine.

Previously, dinuclear Ru(I) and Ru(II) complexes with carboxylate, hydrido, silyl, phosphane, arene, cyclopentadienyl

**Table 1** Cyclopropanation of olefins by EDA catalyzed by **2**<sup>a</sup>

Entry	Substrate	T, °C	Addition of EDA, h	Cyclopropanation <sup>b</sup>		EDA dimerisation <sup>c</sup>		Cyclopropanes/dimers molar ratio
				Yield, %	<i>trans/cis</i>	Yield, %	<i>cis/trans</i>	
A	Styrene	25	2	3	74:26	25	88:12	0.2:1
B	Styrene	70	2	66	71:29	45	88:12	2.4:1
C	Styrene	70	4	77	68:32	40	88:12	3.2:1
D	Styrene	70	6	84	70:30	30	89:11	4.7:1
E	Styrene	90	6	92	69:31	13	89:11	11.5:1
F	<i>p</i> -Methoxystyrene	90	6	100	75:25	7	90:10	25:1
G	<i>p</i> -Fluorostyrene	90	6	95	70:30	9	89:11	19:1
H	Pentafluorostyrene	90	6	68	74:26	21	95:5	5.2:1
I	1,1-Diphenylethene	90	6	100	—	3	92:8	50:1

<sup>a</sup> Reactions were carried out under Ar in toluene using 1 equiv. of olefin (1 M), 1.2 equiv. of EDA (1.2 M) added by using a syringe pump over the desired time and 0.1 mol% catalyst (1 mM). <sup>b</sup> Yield of cyclopropanation products is based on the amount of the substrate. <sup>c</sup> Total yield of diethyl maleate and diethyl fumarate is based on the EDA amount.



Table 2 N–H insertion of EDA into amines catalyzed by 2<sup>a</sup>

Entry	Substrate	[2], mM	Reaction time, h	Yield, <sup>b</sup> %	RNHCH <sub>2</sub> COOEt/ RN(CH <sub>2</sub> COOEt) <sub>2</sub> ratio
J	Aniline	0.2	2.5	43	100 : 0
K	Aniline	1	2.5	100	83 : 17
L	<i>p</i> -Methylaniline	1	17	100	79 : 21
M	<i>p</i> -Chloroaniline	1	7	100	83 : 17
N <sup>c</sup>	2-Methoxyethylamine	1	30	58	0 : 100
O	Morpholine	1	6	90	—

<sup>a</sup> Reactions were carried out under Ar in toluene at 90 °C using 1 equiv. of amine (1 M), 1.2 equiv. of EDA (1.2 M) added by using a syringe pump over 2 h. <sup>b</sup> Yield is based on the amine amount. <sup>c</sup> Reaction temperature: 70 °C.

and multidentate nitrogen ligands have been used as catalysts for carbene transfer reactions.<sup>28</sup> To the best of our knowledge, carbene transfer reactions catalyzed by Ru in the high oxidation state are rare. Simonneaux and coworkers have used Ru(vi) dioxo porphyrin complexes for the cyclopropanation of styrenes, but active ruthenium carbene species was formed after the reduction of Ru(vi) to Ru(II) complexes with EDA.<sup>29</sup> Similarly, Gross and co-workers proposed that  $\mu$ -oxo diiron(IV) and mononuclear Fe(IV) corrole complexes should be initially reduced to the Fe(III) state to react with EDA.<sup>30</sup> In the present case, Ru(IV)=C=Ru(IV) phthalocyaninate appears to retain a high oxidation state. For this reason, the activation of EDA occurs only at elevated temperatures. Our attempts to detect a putative active carbene complex formed by 2 were unsuccessful.

In conclusion, although several types of ruthenium complexes have emerged as suitable catalysts for carbene transfer reactions,<sup>3,28</sup>  $\mu$ -carbido diruthenium macrocyclic complexes have not been previously considered as catalysts. The original interest in the  $\mu$ -carbido complex 2 was fuelled by the observation of the particular catalytic properties of the related  $\mu$ -nitrido and  $\mu$ -oxo complexes.<sup>19–25</sup> This study represents the first example of the catalytic application of dimeric  $\mu$ -carbido Ru(IV) phthalocyaninate exemplified by the carbene insertion reactions into olefinic bonds and N–H bonds of amines. Although the catalytic activity is still modest, the results obtained suggest that  $\mu$ -carbido diruthenium phthalocyanine can be added to the family of catalytically active single-atom bridged bimetallic macrocyclic complexes and might find interesting applications in catalysis. Recent results from Che's group on the remarkable catalytic properties of Ru(II) porphyrin complexes bearing N-heterocyclic carbene ligands in the carbene and nitrene transfer reactions<sup>31</sup> support the validity of our approach. Apart from the catalytic applications, the reported approach to  $\mu$ -carbido ruthenium(IV) complexes might also attract attention from the viewpoint of elaboration of novel optoelectronic materials.<sup>32</sup>

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- (a) D. Intrieri, A. Caselli, F. Ragaini, P. Macchi, N. Casati and E. Gallo, *Eur. J. Inorg. Chem.*, 2012, **2012**, 569–580; (b) P. Fackler, S. M. Huber and T. Bach, *J. Am. Chem. Soc.*, 2012, **134**, 12869–12878; (c) K.-H. Chan, X. Guan, V. K.-Y. Lo and C.-M. Che, *Angew. Chem., Int. Ed.*, 2014, **53**, 2982–2987.
- (a) Z. Gross and S. Ini, *Inorg. Chem.*, 1999, **38**, 1446–1449; (b) C.-J. Liu, W.-Y. Yu, C.-M. Che and C.-H. Yeung, *J. Org. Chem.*, 1999, **64**, 7365–7374; (c) C. Wang, K. V. Shalyaev, M. Bonchio, T. Carofiglio and J. T. Groves, *Inorg. Chem.*, 2006, **45**, 4769–4782.
- D. Intrieri, D. M. Carminati and E. Gallo, in *Handbook of Porphyrin Science*, ed. K. M. Kadish, K. M. Smith and R. Guilard, World Scientific, Singapore, 2016, pp. 1–99.
- P. Zardi, D. Intrieri, D. M. Carminati, F. Ferretti, P. Macchi and E. Gallo, *J. Porphyrins Phthalocyanines*, 2016, **20**, 1156–1165.
- (a) I. Nicolas, P. Le Maux and G. Simonneaux, *Tetrahedron Lett.*, 2008, **49**, 5793–5795; (b) S. Fantauzzi, A. Caselli and E. Gallo, *Dalton Trans.*, 2009, 5434–5443; (c) W. Xiao, J. Wei, C.-Y. Zhou and C.-M. Che, *Chem. Commun.*, 2013, **49**, 4619–4621.
- M. W. Wolf, D. A. Vargas and N. Lehnert, *Inorg. Chem.*, 2017, **56**, 5623–5635.
- A. B. Sorokin, *Chem. Rev.*, 2013, **113**, 8152–8191.
- H.-H. Liu, Y. Wang, Y.-J. Shu, X.-G. Zhou, J. Wu and S.-Y. Yan, *J. Mol. Catal. A: Chem.*, 2006, **246**, 49–52.
- (a) T. Rawling and A. M. McDonagh, *Coord. Chem. Rev.*, 2007, **251**, 1128–1157; (b) Y. G. Gorbunova, Y. Y. Enakieva,



- S. G. Sakharov and A. Y. Tsivadze, *J. Porphyrins Phthalocyanines*, 2003, **7**, 795–800.
- 10 (a) M. S. Rodríguez-Morgade, M. Planells, T. Torres, P. Ballester and E. Palomares, *J. Mater. Chem.*, 2008, **18**, 176–181; (b) A. N. Cammidge, G. Berber, I. Chambrier, P. W. Hough and M. J. Cook, *Tetrahedron*, 2005, **61**, 4067–4074.
- 11 Y. Y. Enakieva, Y. G. Gorbunova, A. Y. Tsivadze, C. Stern and R. Guillard, *J. Porphyrins Phthalocyanines*, 2007, **11**, 883–890.
- 12 S. Omiya, M. Tsutsui, E. F. Meyer, I. Bernal and D. L. Cullen, *Inorg. Chem.*, 1980, **19**, 134–142.
- 13 A. Kienast, L. Galich, K. S. Murray, B. Moubaraki, G. Lazarev, J. D. Cashion and H. Homborg, *J. Porphyrins Phthalocyanines*, 1997, **1**, 141–157.
- 14 (a) D. O. Oluwole, A. V. Yagodin, N. C. Mkhize, K. E. Sekhosana, A. G. Martynov, Y. G. Gorbunova, A. Y. Tsivadze and T. Nyokong, *Chem. – Eur. J.*, 2017, **23**, 2820–2830; (b) A. G. Martynov, J. Mack, B. P. Ngoy, T. Nyokong, Y. G. Gorbunova and A. Y. Tsivadze, *Dyes Pigm.*, 2017, **140**, 469–479.
- 15 D. Braga, F. Grepioni, P. J. Dyson, B. F. G. Johnson, P. Frediani, M. Bianchi and F. Piacenti, *J. Chem. Soc., Dalton Trans.*, 1992, 2565–2571.
- 16 C. Li, J. Xu, J. Zhao, D. Tian and R. B. King, *Dalton Trans.*, 2010, **39**, 10697–10701.
- 17 (a) L. Ma, G. K. Williams and J. R. Shapley, *Coord. Chem. Rev.*, 1993, **128**, 261–284; (b) S. Takemoto and H. Matsuzaka, *Coord. Chem. Rev.*, 2012, **256**, 574–588.
- 18 A. Kienast, C. Bruhn and H. Homborg, *Z. Anorg. Allg. Chem.*, 1997, **623**, 967–972.
- 19 (a) H. M. Neu, V. V. Zhdankin and V. N. Nemykin, *Tetrahedron Lett.*, 2010, **51**, 6545–6548; (b) O. V. Zalomaeva, I. D. Ivanchikova, O. A. Kholdeeva and A. B. Sorokin, *New J. Chem.*, 2009, **33**, 1031–1037; (c) C. Pergrale and A. B. Sorokin, *C. R. Chimie*, 2000, **3**, 803–810.
- 20 P. Afanasiev and A. B. Sorokin, *Acc. Chem. Res.*, 2016, **49**, 583–593.
- 21 (a) Ü. İsci, A. S. Faponle, P. Afanasiev, F. Albrieux, V. Briois, V. Ahsen, F. Dumoulin, A. B. Sorokin and S. P. de Visser, *Chem. Sci.*, 2015, **6**, 5063–5075; (b) A. B. Sorokin, E. V. Kudrik and D. Bouchu, *Chem. Commun.*, 2008, 2562–2564.
- 22 Ü. İsci, P. Afanasiev, J.-M. M. Millet, E. V. Kudrik, V. Ahsen and A. B. Sorokin, *Dalton Trans.*, 2009, 7410–7420.
- 23 P. Afanasiev, D. Bouchu, E. V. Kudrik, J.-M. M. Millet and A. B. Sorokin, *Dalton Trans.*, 2009, 9828–9836.
- 24 C. Colomban, E. V. Kudrik, P. Afanasiev and A. B. Sorokin, *J. Am. Chem. Soc.*, 2014, **136**, 11321–11330.
- 25 L. X. Alvarez, E. V. Kudrik and A. B. Sorokin, *Chem. – Eur. J.*, 2011, **17**, 9298–9301.
- 26 (a) P. Tang and Y. Qin, *Synthesis*, 2012, **44**, 2969–2984; (b) K. Lang and J. W. Chin, *Chem. Rev.*, 2014, **114**, 4764–4806.
- 27 B. J. Anding and L. K. Woo, *Organometallics*, 2013, **32**, 2599–2607.
- 28 G. Maas, *Chem. Soc. Rev.*, 2004, **33**, 183–190.
- 29 E. Galardon, P. Le Maux and G. Simonneaux, *Chem. Commun.*, 1997, 927–928.
- 30 L. Simkhovich, A. Mahammed, I. Goldberg and Z. Gross, *Chem. – Eur. J.*, 2001, **7**, 1041–1055.
- 31 K.-H. Chan, X. Guan, V. K.-Y. Lo and C.-M. Che, *Angew. Chem., Int. Ed.*, 2014, **53**, 2982–2987.
- 32 Y. G. Gorbunova, A. D. Grishina, A. G. Martynov, T. V. Krivenko, A. A. Isakova, V. V. Savel'ev, S. E. Nefedov, E. V. Abkhalimov, A. V. Vannikov and A. Y. Tsivadze, *J. Mater. Chem. C*, 2015, **3**, 6692–6700.

