Halogenation of the Hexaphosphabenzene Complex \([\text{Cp}^*\text{Mo} \_2(\mu_1 \eta^5: \eta^6-P_6)]\): Snapshots on the Reaction Progress

Anna Garbagnati,[a] Michael Seidl,[a] Gábor Balázs,[a] and Manfred Scheer*[a]

Abstract: The oxidation of \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)]\) (1) with halogens or halogen sources was investigated. The iodination afforded the ionic complexes \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_1 \eta^1: \eta^1-P_2)\mu_2(\eta^1-P_3)\mu_2(\eta^1-P_4)]\) (X = I, Br) (2) and \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_2-P_3)\mu_1(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (3), while the reaction with PBr_3 led to the complexes \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_2-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (4) \([\text{Cp}^*\text{MoBr}_2(\mu_1 \eta^1: \eta^1-P_3)(\mu_1 \eta^1-P_3)\mu_2(\mu_2-P_3)]\) (5) and \([\text{Cp}^*\text{Mo}_2(\mu_2-PBr_3)\mu_2(\mu_2-PBr_3)]\) (6). The reaction of 1 with the far stronger oxidizing agent PCl_3 was followed via time- and temperature-dependent \(^{31}\text{P}(^1\text{H})\) NMR spectroscopy. One of the first intermediates detected at 193 K was \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_2-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (7) which rearranges upon warming to \([\text{Cp}^*\text{Mo}_2(\mu_2-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (8) and \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_2-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (9) \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_2-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (10) and \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_6)(\mu_2-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (11), which could be isolated at room temperature. All complexes were characterized by single-crystal X-ray diffraction, NMR spectroscopy and their electronic structures were elucidated by DFT calculations.

Introduction

The halogenation of white phosphorus is the first step on an industrial scale to transform P_4 to organophosphorus derivatives. First publications on the halogenation of white phosphorus date back more than 120 years.[1,2] In 1940, Wyllie et al. proved that the reaction of P_4 with I_2 leads to P_3I_4 or P_4I_6, depending on the used stoichiometry, while the reaction of P_4 with Br_2 leads to P_3Br_5.[3] Based on these results, in 1994, Tattershall et al. reported four series of compounds resulting from the reaction of P_4 with I_2, Br_2 or ICl that were identified by NMR spectroscopy.[4] Later on, Stopponi et al. presented the first example of a halogenation of coordinated white phosphorus in the coordination sphere of a transition metal by iodoination, which resulted in the monocation \([\text{Cp}^*\text{Ru}(\text{PPh}_3)_2(\mu_1 \eta^5: \eta^6-P_5)\mu_2(\eta^1-P_6)]\).[5] In 1999, Peruzzini et al. reported the ruthenium-mediated halogenation of white phosphorus, resulting in the complex \([\text{Cp}^*\text{Ru}(\text{PCy}_3)_2(\mu_1 \eta^5: \eta^6-P_3)\mu_2(\eta^1-P_5)\mu_2(\eta^1-P_6)]\) (Cp^*Ru) bearing the unprecedented P_5Cl_4 moiety.[6] Recently, the stepwise degradation of white phosphorus coordinated to a Ru(II) complex upon the reaction with iodine was postulated by DFT computations.[7] The key role of the metal was demonstrated since the proposed mechanism differs significantly from the concerted one that is valid for uncoordinated white phosphorus.[8] As an alternative access, P_4 moieties already converted to polyphosphorus complexes might be a valuable approach to functionalized polyphosphorus complexes.

Our recent study on the iodination of the cyclo-E_5 complexes \([\text{Cp}^*\text{M}(\eta^5-E_5)]\) (M = Fe, Ru; E = P, As)[9] has shown that this is a powerful method for the high-yield synthesis of new types of functionalized polyphosphotin compounds (Scheme 1b, red arrow). By examining different halogen sources, the halogenation of the tetrahedrane compound \([\text{Cp}^*\text{Mo}(\text{CO})_3(\mu_1 \eta^5: \eta^6-P_5)]\) proved to lead to various reaction products (Scheme 1a, red arrow).[10] These studies clearly show the different reactivities of polyphosphorus complexes with oxidants such as halogens towards an alternative one-electron oxidation. Thus, the oxidation of \([\text{Cp}^*\text{Mo}(\text{CO})_3(\mu_1 \eta^5: \eta^6-P_5)]\) leads selectively to the dicaticonic complex \([\text{Cp}^*\text{Mo}(\text{CO})_3(\mu_1 \eta^5: \eta^6-P_5)]^{2+}\) (Scheme 1a, B), while the halogenation yields, depending on the used stoichiometry and halogen, C-E (Scheme 1a). Similarly, a substantial difference in the one-electron oxidation of \([\text{Cp}^*\text{Fe}(\eta^5-P_5)]\) and its oxidation with halogens was realized. While the oxidation leads to the dicaticonic complex \([\text{Cp}^*\text{Fe}(\eta^5-P_5)]^{2+}\) (Scheme 1b, G),[12] the reaction with I_2 yields the nortricyclic derivative H (Scheme 1b). Since in triple-decker complexes the middle deck is stabilized by two metal fragments, a higher stability of the products in the reaction with halogens is expected, possibly enabling the identification of intermediates and their isolation along the reaction pathway.

Therefore, the redox-active compound \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_5)]\) (1)[13] was chosen for a detailed study of its halogenation. The cyclo-voltammogram of this 28 VE complex reveals a reversible one-electron oxidation in which a 27 VE product results in a distorted cyclo-P_4 ligand in a bis-allylic arrangement (Scheme 1c, I).[14] Herein we report on the oxidation of the hexaphosphabenzene complex \([\text{Cp}^*\text{Mo}_2(\mu_1 \eta^5: \eta^6-P_5)]\) (1) by halogens and

---

[a] A. Garbagnati, Dr. M. Seidl, Dr. G. Balázs, Prof. Dr. M. Scheer
Institute of Inorganic Chemistry
University of Regensburg
93040 Regensburg (Germany)
E-mail: manfred.scheer@chemie.uni-regensburg.de
Homepage: https://www.uni-regensburg.de/chemie-pharmazie/
anorganische-chemie-scheer

© 2022 The Authors. Chemistry - A European Journal published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution Non-Commercial NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

Chem. Eur. J. 2022, 28, e202200669 (1 of 9) © 2022 The Authors. Chemistry - A European Journal published by Wiley-VCH GmbH

www.chemeurj.org
The reaction of 1 with an excess of iodine (6 equiv.) in CH\textsubscript{2}Cl\textsubscript{2} followed by the layering of the reaction solution with n-pentane, leads to [(Cp*Mo)\textsubscript{2}(μ-I\textsubscript{3})(μ-I\textsubscript{2})(I\textsubscript{2})](I\textsubscript{2}) as a red crystalline compound in 54\% isolated yield (Scheme 2).

When a stoichiometric amount of I\textsubscript{2} was used (3 equiv.), a few crystals of the similar complex 2-I\textsubscript{2} in which I\textsubscript{2} is replaced by I\textsubscript{3} as counterion were isolated, together with [(Cp*Mo)\textsubscript{2}(μ-I\textsubscript{2})(μ-I\textsubscript{3})(μ-Cl\textsubscript{2})](Cl\textsubscript{2}) (3) as black blocks in a crystalline yield of 2\% (Scheme 2, cf. Supporting Information). The ESI-MS spectrum of the latter reaction solution shows the molecular ion peak of 2 and 3, together with one of the paramagnetic complex [(Cp*Mo)\textsubscript{2}(μ-I\textsubscript{3})][I\textsubscript{2}]. The latter compound was already described by Poli et al.\textsuperscript{[15]} Possible other products as for instance PBr\textsubscript{6} or PCl\textsubscript{6} could not be detected in the \textsuperscript{31}P{\textsuperscript{1}H} NMR spectrum of the reaction solution which shows only the signals of 2 (see below). The formation of 3 could not be ascertained by \textsuperscript{31}P NMR spectroscopy due it is paramagnetic nature. Since no signals of the starting material were detected, its full conversion can be assumed. The variable temperature (VT) \textsuperscript{31}P{\textsuperscript{1}H} NMR spectrum of this reaction solution recorded from −80°C to room temperature shows that the formation of 2 starts already at low temperatures, with 2 being the only P-containing diamagnetic product that could be detected. The spectra at higher temperatures are silent because 2 precipitates completely from the solution already at low temperatures (cf. SI for VT-\textsuperscript{31}P{\textsuperscript{1}H} NMR) and the remaining products are paramagnetic.

Our study of the halogenation of [(CpMo(CO)\textsubscript{2}(μ-I\textsubscript{3})-P\textsubscript{2}J\textsubscript{2}J\textsubscript{2}] showed that the nature of the halogen (I\textsubscript{2} vs. Br\textsubscript{2}) plays a decisive role regarding the type of the resulting compounds.\textsuperscript{[10]} Hence, the reaction of [(CpMo(CO)\textsubscript{2}(μ-I\textsubscript{3})-P\textsubscript{2}J\textsubscript{2}J\textsubscript{2}]] (1) with PBr\textsubscript{3} as a bromine source was carried out. Due to the higher reactivity of bromine (as compared to iodine), the reaction of 1 with an excess of PBr\textsubscript{3} (6 equiv.) in CH\textsubscript{2}Cl\textsubscript{2} was carried out at −40°C and the reaction solution was slowly warmed up to −20°C. Precipitation of the concentrated reaction solution with cold n-pentane led to a green precipitate which was dissolved in THF and layered with toluene affording a few crystals of [(Cp*Mo)\textsubscript{2}(μ-I\textsubscript{3})-P\textsubscript{2}J\textsubscript{2}J\textsubscript{2}J\textsubscript{2}J\textsubscript{2}] (4) (2\% yield). The supernatant mother liquor was decanted off and, while warming up to room temperature, crystals of the neutral species [(Cp*MoBr\textsubscript{3})(μ-I\textsubscript{3})-P\textsubscript{2}J\textsubscript{2}J\textsubscript{2}J\textsubscript{2}J\textsubscript{2}] (5) were formed in 17\% yield. Performing the reaction under the same conditions but evaporating all volatiles at −10°C, washing the residue with n-pentane and toluene and finally recrystallizing from a mixture of CH\textsubscript{2}Cl\textsubscript{2}/n-pentane, crystals of [(Cp*Mo)\textsubscript{2}(μ-PBr\textsubscript{3})(μ-Cl\textsubscript{2})](PBr\textsubscript{6}) (6) could be isolated (9\% yield; Scheme 2). Additionally, also a few crystals of the known side product [(Cp*MoBr\textsubscript{3})(μ-PBr\textsubscript{3})]\textsubscript{2}\textsuperscript{[16]} were formed. The \textsuperscript{31}P{\textsuperscript{1}H} NMR spectrum of the reaction solution shows, among the signals corresponding to 4\textsuperscript{[17]} and 6, a broad singlet at 230 ppm corresponding to PBr\textsubscript{6} which overlaps with one of the two signals of 6. Signals corresponding to 5 could not be detected in the \textsuperscript{31}P NMR spectrum of the freshly prepared reaction solution, but were only detected after storing the sample at room temperature for five days. This indicates that 5 is not an initial product of the reaction of 1 with PBr\textsubscript{3}. Preparing an NMR sample by mixing a precooled solution of 1 and PBr\textsubscript{3} and performing a VT-\textsuperscript{31}P{\textsuperscript{1}H} NMR experiment (starting at −80°C) shows the formation of a very complex reaction mixture (cf. SI) from which no known complexes could be identified. By warming to room temperature, signals corresponding to 6 could be detected. Since the signal of PBr\textsubscript{6} is always detected when using PBr\textsubscript{3} as a reagent, the question arises whether it results from the halogenation of 1. \textsuperscript{31}P NMR spectroscopic investigations showed that only about 30\% of the PBr\textsubscript{6} originates from PBr\textsubscript{3} while the remaining 70\% follows from the bromination of 1 (see Supporting Information).

Against the background that the reaction of 1 towards a bromine source was predictably more complex than the one with iodine, the question arises as to what would be the
difference in the reactivity towards an even stronger halogenating agent as for instance chlorine. Therefore, a time-dependent $^3$P{$^1$H} NMR study of the reaction of 1 with an excess of PCl$_5$ (6 equiv.) was carried out at 193 K (Figure 1a). The signal of 1 could not be detected, which proves that its conversion is complete already at 193 K after fifteen minutes. The first $^3$P{$^1$H} NMR spectrum ($t_1 = 15$ minutes) shows four resonances centered at $\delta = 420.8$, 329.3, 145.1 and $-361.7$ ppm in a 1:2:2:1 integral ratio, corresponding to an AMM'O'O'X spin system (Figure 1a,b) which can be assigned to 7, based on its similarity with 2 (see below). In addition, a singlet corresponding to PCl$_3$ ($\delta = 220.0$ ppm) and a singlet at 6.5 ppm which could not be assigned were detected. 7 could not be isolated due to its high instability. Attempts to crystallize it led to the isolation of [(Cp*Mo)$_2$(µ,η$_3$:η$_3$-P)$_3$(µ-PCl)$_2$][(PCl)$_6$] (8) instead (74 % yield, scheme 2). Based on the $^3$P NMR spectroscopic data, the first product of the reaction of 1 with PCl$_5$ is 7 which then converts to 8, where its signals start to appear in the time-dependent NMR study after one hour ($t_2 = 1$ h; figure 1a).

Solutions of 8 in CH$_2$Cl$_2$ at room temperature are stable for less than one hour, afterwards the color of the solution starts to change from bright red to dark brown. Its decomposition was monitored by NMR spectroscopy (see Supporting Information). The $^3$P{$^1$H} NMR spectrum of the crystals of 8 dissolved in

**Scheme 2.** Reaction of [(Cp*Mo)$_2$(µ,η$_3$:η$_3$-P)$_3$] with I$_2$, PBr$_3$, and PCl$_5$. 

---

Chem. Eur. J. 2022, 28, e202200669 (3 of 9) © 2022 The Authors. Chemistry - A European Journal published by Wiley-VCH GmbH
CD₂Cl₂ at room temperature reveals after seven hours its complete decomposition and formation of [(Cp*Mo)₂(μ-PCl₂)(μ-Cl)]₂ (9), [(Cp*MoCl)₂(μ,η₃:η₃-P₃)(μ-PCl₂)] (10) and PCl₃ (Figure 2). Moreover, the intensity of the signal corresponding to PCl₃ (220.2 ppm) increases with the temperature, while the one of [PCl₆]⁻ decreases until it disappears completely at room temperature (cf. SI for VT ³¹P{¹H} NMR). By performing the reaction of 1 with PCl₅ directly at room temperature, 9 and 10 can be isolated in 3% and 4% crystalline yield, respectively (Scheme 2).

The ³¹P{¹H} NMR spectrum of the reaction solution at 25 °C shows the characteristic signals of 9 (δ = 317.2 ppm), 10 (see below) and PCl₃ (δ = 220.2 ppm) among other signals that could not be assigned (cf. SI). Roughly 78% of the PCl₃ originates from 1, which reflects the low yields of 9 and 10. Attempts to isolate other products of the chlorination led to the isolation of the 30 VE cationic triple-decker compound [(Cp*Mo)₂(μ,η₄:η₄-P₄)(μ-PCl₂)](Cp*MoCl₄) (11) (Scheme 2). 11 is well soluble in CD₂Cl₂ but paramagnetic (cf. Supporting Information) and therefore could not be detected by NMR spectroscopy, but was identified by single crystal X-ray diffraction analysis. In the ¹H NMR spectrum of 11, the signal of the anion [Cp*MoCl₄]⁻ in 11 could be detected at −13.9 ppm as a broad singlet (ω₁/₂ = 170 Hz), which is in line with the reported chemical shift. When 1 was reacted with three equiv. of PCl₅, the neutral analogue of 11, i.e. [(Cp*Mo)₂(μ,η₃:η₃-P₃)(μ-PCl₃)] (12), could be isolated in 10% yield. The 31VE triple-decker complex 12 is paramagnetic, but no signals could
be detected by EPR spectroscopy, probably due to its triplet spin state. Crystals of 11 were alternatively obtained by layering a solution of 8 with n-pentane in CH₂Cl₂ at room temperature after few days. Therefore, together with 9 and 10, 11 represents another conversion product of 8 (Scheme 2). Additional proof of this is provided by the ¹H NMR spectrum of crystals of 8 dissolved in CD₂Cl₂, which also shows, after 15 days at room temperature, the broad singlet of the counterion of 11, [Cp*MoCl]⁻ (cf. Supporting Information).²¹

The ³¹P NMR spectra of 2 and 7 are very similar, both of them showing an AMM’O’OX spin system (cf. Supporting Information). The central phosphorus atom of the allylic-like P₃ unit (P⁰) resonates at high field (~327 ppm for 2 and ~362 ppm for 7), while the peripheral P atoms (P⁹/P⁷) resonate at lower field (349 ppm for 2 and 382 ppm for 7) and show the largest Jₚp coupling constant (~380 Hz). Similar chemical shifts and coupling constants were found for the allylic-like P₃ unit in the complexes 5, 10 and 8 (for details see Supporting Information), although 5 shows an ADHXX spin system (Figure 3, top) due to the chemically inequivalent peripheral P atoms of the allylic-like P₃ unit. The central P atom (P⁰) of the P₃X₃ subunit resonates at low field (380 ppm for 2 and 421 ppm for 7), while the peripheral P atoms (P⁹/P⁷) resonate at moderately higher field (5 ppm for 2 and 145 ppm for 7) and show a smaller Jₚp coupling constant (~280 Hz; Figure 1b). Within the PBrPBr unit of 5, the Jₚp coupling of 420 Hz is rather large and an additional large coupling (Jₚp₂=70 Hz) is observed within the P₃ unit. Similarly, P–P couplings can be detected between the PCl₃ and the P₃ units (up to 35 Hz in 8 (Figure 1c) and 10 (up to 41 Hz, Figure 3, bottom). Additionally, the resonance signal of the PCl₃ anion in 8 is observed at ~296 ppm in the ³¹P NMR spectrum. Compound 8 shows rather broad signals at room temperature, which sharpen by lowering the temperature to ~40 °C (Figure 1c).

The ³¹P(¹H) NMR spectrum of 6 shows two doublets with a coupling constant of 38 Hz, corresponding to the two non-equivalent phosphorus atoms. The signal at the highest field can be assigned to the PH ligand which splits in the ³¹P NMR spectrum into a doublet due to the coupling with the proton (JₚH=444 Hz). For 9, only one singlet was detected (cf. Supporting Information). The ³¹P NMR chemical shifts and coupling constants for all complexes were determined by iterative simulation of the experimental spectra (see Supporting Information).

Apart from 7 which is extremely unstable even at low temperatures in solution and could not be isolated, the solid-state structures of all other products were determined by single crystal X-ray diffraction analysis (Figure 4), revealing that the halogenation of the 28VE cyclo-P₆-containing triple-decker complex [[(Cp*Mo)(η⁷-C₆H₅)P₃]⁺] (1) leads to the formation of dinuclear monocations and neutral species which, in most cases, retain their triple-decker geometry. However, in some cases, degradation to [[Cp*MoBr₂(μ-Br)]₃]⁻ ([Cp*MoO]⁻) or [Cp*MoX₃]-, the latter being observed as an anion in 4 and 11, was detected. For all complexes, the Mo–Mo bond lengths are below the sum of their covalent radii (3.08 Å)²² and longer than the corresponding distance in the neutral cyclo-P₆ complex 1 (2.647(1) Å)¹⁵ and in the related monocation [[(Cp*Mo)(η⁷-C₆H₅)P₃]⁺][FAI]⁻ ([FAI]⁻=[FAI(OOCF₂OOCF₂OOCF₂)]⁻), 2.661(8) Å).²⁶ They vary from 2.691(2) Å in 9 to 2.920(6) Å in 10. The only exception is observed within 4 with a Mo–Mo distance of 2.579(6) Å. The Cp* ligands in the compounds 2-I₃, 3, 4, 6, 8, 9 and 11 are almost coplanar to each other, being only minimally tilted (tilt angle of 1° to 7°). In compounds 5 and 10, the coplanarity of the ligands is lost, and the Cp* ligands are tilted by 40° and 38°, respectively.

The molecular structure of 2-I₃ shows an allylic-P₃ and a P₃ ligand each of them bridging the two [Cp*Mo] fragments (Figure 4). In the P₃I₁ unit, the central P atom does not coordinate to molybdenum. Compared to the P–P bond lengths in 1¹¹ (average: 2.171(3) Å and in the range of P–P single bonds (2.22 Å)²³, the P₃-P₄ (2.139(5) Å) and P₄-P₅ (2.138(6) Å) distances are shortened. Similar bond lengths were observed for the cationic complex [[(Cp*Mo)(η⁷-C₆H₅)P₃][FAI]⁻]¹⁶ whose cyclo-P₆ undergoes a bis-allylic distortion upon one electron oxidation (average: 2.136(10) Å). The P₁-P₂ (2.216(5) Å) and the P₁-P₆ (2.220(5) Å) distances in the P₃I₃ ligand are longer than the one in 1 and correspond to P–P single bonds, while the distance between P2 and P₆ with 2.459(5) Å is too long for a usual single bond, but considerably below the sum of the van der Waals radii (3.80 Å).²² DFT calculations for compound 2-I₃ reproduce this distance (2.434 Å) well, but no bonding interaction could be detected between these two P atoms (the Mayer bond order (BO) is lower than 0.1 and no orbital overlap occurs). The P–P distances between the two P₃ ligands are rather long (P₂–P₃ 2.652(5) Å and P₅–P₆ 2.665(5) Å). Nevertheless, DFT calculations indicate the presence of a P–P interaction as shown by BOs of 0.16 and 0.18 for P₂–P₃ and P₅–P₆, respectively (see also Supporting Information). A similar cyclo-P₆ moiety was recently postulated by DFT computations as one of the intermediates involved in the last steps of the iodine-induced stepwise degradation of the P₃ ligand in [Cp*Ru(dppe)(η⁷-P₃)]⁻ but without any experimental evidence. Therefore, 2-I₃ represents the first example of an isolated polyphosphorus complex bearing a P₃ ligand. The presence of an allylic P₃ ligand is recurrent among the products of the halogenation of 1, as in 4, 5, 8 and 10, which will be discussed together therefore. In the allylic P₃ ligand of 4, the P₁–P₂ (2.126(2) Å) and the P₂–P₃ (2.118(19) Å) bond lengths are shortened compared to the P–P

**Figure 3.** Selected signals of the ³¹P(¹H) NMR spectra of 5 (top) and 10 (bottom) [CD₂Cl₂, 300 K].

---

Chem. Eur. J. 2022, 28, e202200669 (5 of 9)

© 2022 The Authors. Chemistry - A European Journal published by Wiley-VCH GmbH
Figure 4. Molecular structures of 2-I, 3, 4, 5, 6, 8, 9, 10 and 11 with thermal ellipsoids at 50% probability level. Hydrogen atoms and the counterions of 2-I, 3, 4, 8 and 11 are omitted for clarity. In case of disorder only the major parts are depicted. Selected bond lengths: 2I: Mo1–Mo2: 2.722(15) Å, P1–P2: 2.216(5) Å, P1–P6: 2.220(5) Å, P3–P4: 2.139(5), P4–P5: 2.138(6) Å; 3: Mo1–Mo2: 2.743(8) Å, P2A–P3A: 2.243(7) Å, P3–P3': 2.162(4); 4: Mo1–Mo2: 2.579(6) Å, P1–P2: 2.126(2) Å, P2–P3: 2.118(19) Å; 5: Mo1–Mo2: 2.919(7) Å, P1–P2: 2.260(2) Å, P3–P4: 2.174(2) Å, P4–P5: 2.128(2) Å; 6: Mo1–Mo2: 2.709(3) Å, 8: Mo1–Mo2: 2.728(2) Å, P2–P3: 2.105(4) Å, P3–P4: 2.101(4) Å; 9: Mo1–Mo2: 2.691(2) Å; 10: Mo1–Mo1': 2.920 (6) Å, P2–P3: 2.163 (2) Å, P3–P4 2.123 (3) Å; 11: Mo1–Mo2: 2.759(4) Å, P2–P3: 2.210(9) Å, P4–P5: 2.197(8), P3–P4: 2.155(9) Å.
bond lengths in 1 (average: 2.171(3) Å). In the case of 5, the P₃ ligand is distorted (P₃-P₄ = 2.174(2) Å; P₄-P₅ = 2.128(2) Å) and additionally a P-Br₃ ligand bridges the two (Cp²*MoBr₃) fragments in an end-on coordination mode with a P–P bond length that is in the range of a P–P single bond (P₁–P₂ = 2.260(2) Å). Several diphosphines of the type RP₃Br₃ were reported, for example with R = Bu by Baudler et al.[24] R = CCl₃[25] or R = CN[26] but no P₃Br₃ unit as a ligand attached to a metal fragment is known. Thus, the one in 5 is the first reported example. The P₁ ligand in 8 is in line with what was observed for the analog P₃ units in 2–Iₚ, 4 and 5, with P₂–P₃ = 2.105(4) Å and P₃–P₄ = 2.101(4) Å. The average distance from this unit and the PCl₃ groups (2.663(7) Å) suggests the presence of P–P interactions between them. The solid-state structure of 10 resembles the one observed for 5, containing a distorted allylic P₃ ligand (P₂–P₃: 2.163(2) Å and P₃–P₄: 2.123(2) Å) bridging between two (Cp²*MoCl₃) units. The short distance between the P₃ ligand and the PCl₃ group (P₁–P₂ = 2.577(19) Å) indicates an interaction which is also reflected in a rather large J_pₐ coupling constant between these nuclei. The short P₁–P₂ distance (2.551 Å) is well reproduced by DFT calculations and is accompanied by a BO of 0.22 indicating the presence of P···P interactions between them. The P–P interaction (see below).

The solid-state structure of 3 reveals a cisoid-P₃ and a PI₂ bridging ligand separated from each other by 2.596(9) Å. The P₂–P₃ ( = P₂–P₃³) = 2.243(7) Å and P₃–P₄ ( = 2.162(4) Å) bond lengths in the cisoid-P₃ ligand all lie in the range of P–P single bonds. Therefore, it cannot be described as a tetraphosphenyl-1,3-diene-like ligand, contrary to the analog cisoid-P₄ ligands in complexes [(Cp²*Fe)₂(μ₃-P₄-P₄)][28] [(Cp²*Fe)₂(μ₃-P₄-P₄)]2[29] [(Cp²*Fe)₂(μ₃-P₄-P₄)] (Cp² = C₅H₅(SiMe₃)₅). The cisoid-P₃ ligand as middle deck in the 30VE species 11 is similar to the one in 3 with two longer P–P bonds (P₂–P₃ = 2.210(9) Å, P₄–P₅ = 2.197(8) Å) and a shorter one (P₃–P₄ = 2.155(9) Å). The P₁–P₂ and the P₁–P₅ distances in 11 are 2.664(8) Å and 2.6591(7), respectively, indicating a P–P interaction (see below).

The solid-state structure of 6 contains only two P atoms, in the form of a PB₃ and a PHBr bridging ligand, with a nonbonding distance between the two phosphorus atoms of 2.762(9) Å. A similar structure was observed for compound 9, which bears two equivalent bridging PCl₃ ligands, separated from each other by 2.894(6) Å.

In order to investigate the bonding situation in complexes 2–12, DFT calculations at the D4-TTPSSh/(CPCM)/def2-TZVP level were conducted.[31] The geometric parameters of the complexes are well reproduced, including the distances between the different P₃ units in the molecules. In all complexes 2–12, a Mo–Mo bond was detected, being in line with the relatively short Mo–Mo distances. The Mayer bond order (BO) varies from 0.87 in 4 to 0.59 in 5 (Mo–Mo distances 2.574 and 2.892 Å in the optimized geometries, respectively). The intrinsic bonding orbitals[32] representing the Mo–Mo bond in 2 and the bonding within the Mo₃P₃ unit in 4 are depicted in Figure 5.

The NBO[33] analysis is in agreement with the IBO analysis, although only in 4 and 6 an Mo–Mo bond (Mo–Mo 2.579 Å (4) and 2.709 (6)) is predicted by the NBO analysis, while in the other complexes a nonbonding NBO on each Mo with an occupancy of approx. 1e is partitioned instead of a Mo–Mo bonding orbital. Although the P₂–P₆ distance in 2 is rather short, no bonding interaction could be detected by DFT calculations. In contrast, bonding interactions were detected between P₂–P₃ (2.649 Å) and P₅–P₆ (2.628 Å) as shown by BOs of 0.16 and 0.18, respectively. Similar interactions were detected between P₁–P₂ A in 3 (P₁–P₂ A 2.623 Å, BO 0.17; singlet spin state), P₂–P₃ in 5 (2.594 Å, BO 0.17), P₁–P₂ in 8 (2.517 Å, BO 0.24), P₁–P₂ in 10 (2.551 Å, BO 0.22), P₂–P₃ in 11 (2.626 Å, BO 0.18; singlet spin state) and P₂–P₃ in 12 (2.665, BO 0.17). The Interaction Region Indicator (IRI)[34] clearly shows a bonding interaction between the P₃ and the PCl₃ units in 8, among the expected bonds. A plot of IRI in the plane defined by the phosphorus atoms is depicted in Figure 5 showing the regions with notable chemical bond interaction (orange) and areas where weak interactions occur (green). The Electron Localization Function (ELF)[35] and Localized Orbital Locator (LOL)[36] also support these interactions (see Supporting Information). Complexes 3 and 11 are paramagnetic in solutions at room temperature, however, DFT calculations show that the singlet spin state of the cation in 3 and 11 is with 90 and 102 kJ·mol⁻¹, respectively, more stable than the triplet spin state. The overall paramagnetic behavior of 11 might be due to the paramagnetic nature of the counter anions [Cp²*MoCl₄]⁻, having a triplet spin state as determined experimentally.[37]

![Figure 5. Intrinsic bonding orbitals representing the Mo–Mo bond in 2 (top left) and 4 (top right) as well as the Interaction Region Indicator (IRI) plot in the plane defined by the phosphorus atoms (bottom left) and Electron Localization Function (ELF) plot (bottom right) in 8. Blue dots represent (3,–1) critical points.](image-url)
Conclusions

In summary, we showed that the halogenation of \([\text{[Cp}^*\text{Mo}](\mu_3\eta^1\eta^-\text{P}_6)]) (1) proceeds via a very complex pathway leading to a plethora of complexes containing different \(P_n\) units such as \(P_4\), \(P_5\), \(P_6\), and \(P_7\). An excess of halogens/halogen sources leads to phosphorus-free complexes of the type \([\text{CP}^*\text{MoX}_3](X=I, Br, Cl)\) as well as \(PX_4\) (\(X=Br, Cl\)) as final reaction products. Additionally, we showed that besides iodination, which is known to be a powerful tool for the synthesis of new \(P_n\) ligand complexes, bromination and chlorination can also be used for this purpose. Among the products of the iodination of the hexaphosphabenzene complex 1, the novel compound 2 bearing an unprecedented \(P_7\) ligand could be isolated. With a bromine source, complex 5 could be isolated, representing the first example of a compound bearing a \(P_7\)Br unit as a bridging ligand between two Mo centers.

Whereas the products of the one-electron oxidation of 1 showed only a distortion of the hexagonal geometry of the \(P_6\) middle deck, the use of halogens or halogen sources as oxidizing agents afforded a variety of new polyphosphorus compounds bearing synthetically useful novel \(P_nX_m\) units. As expected, the chemoselectivity of the reaction decreased with the enhancement of the oxidizing power of the halogen. However, with a strict control of the temperature it is possible to exert a good control of the reaction even with a stronger oxidant such as the chlorine source \(PCl_3\). First snapshots from the halogenation of the \(P_6\) ligand complex were found, and even though the complete pathway could not be clarified, they gave useful information concerning the progress of the reaction. Thus, first an allylic fragmentation of the cyclo-\(P_6\) unit occurs followed by the monohalogenation of the P atoms of one of the allylic \(P_5\) units. Subsequently, a dihalogenation forming \(PX_4\) units occurs, which is followed by the removal of the P atoms as \(PX_4\) moieties. Only afterwards, the second allylic \(P_5\) unit appears to be halogenated.

This study adds triple-decker complexes to the class of polyphosphorus compounds that can be successfully halogenated and thus functionalized. Therefore, future investigations will focus on the halogenation of heterobimetallic triple-decker compounds as well as of \(E_n\) ligand derivatives that combine the features of triple-decker complexes and separate \(E_n\) units. Moreover, since the halogenation reactions in general have shown to be a powerful tool for the generation of halogen-functionalized polyphosphorus ligands, future studies will also focus on the use of these products for further derivatizations.

Deposition Numbers 2155218 (2-I), 2155219 (3), 2155220 (4), 2155221 (5), 2155222 (6), 2155223 (8), 2155224 (9), 2155225 (10) 2155226 (11) and 2155227 (12) contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service.

Acknowledgements

The Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged for the support within the project Sch384/36-2. Open Access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords: bromine • chlorine • halogenation • hexaphosphabenzene • iodine • phosphorus

[1] J. A. Besson, Compt. Rend. 1897, 124, 1346–1349.
[2] R. Bouloch, Compt. Rend. 1905, 141, 256.
[3] D. Wylle, M. Ritchie, E. B. Ludlom J. Chem. Soc. 1940, 583–587.
[4] B. W. Tattershall, N. L. Kendall Polyhedron 1994, 13, 1517–1521.
[5] P. Barbaro, C. Bazzicalupi, M. Peruzzini, S. Seniori Costantini, P. Stopponi, Angew. Chem. Int. Ed. 2012, 51, 8628–8631.
[6] M. Bispinghoff, Z. Benkó, H. Grützmacher, F. Delgado Calvo, M. Caporalì, M. Peruzzini, Dalton Trans. 2019, 48, 3593–3600.
[7] G. Manca, A. Ienco, Inorg. Chim. Acta 2021, 517, 120205.
[8] C. Mealli, A. Ienco, M. Peruzzini, G. Manca, Dalton Trans. 2018, 47.
[9] H. Brake, E. Peresypkina, A. V. Virovets, M. Piesch, W. Kremer, L. Zimmermann, Ch. Klimas, M. Scheer, Angew. Chem. Int. Ed. 2020, 59, 59, 16241–16246.
[10] A. Garbagnati, M. Seidl, G. Balázs, M. Scheer, Inorg. Chim. Acta. 2021, 50, 5163–5171.
[11] L. Dutsch, M. Fleischmann, S. Welsch, G. Balázs, M. Scheer, Angew. Chem. Int. Ed. 2018, 57, 3256–3261.
[12] M. V. Butovskiy, G. Balázs, M. Bodensteiner, E. V. Peresypkina, A. V. Virovets, J. Sutter, M. Scheer, Angew. Chem. Int. Ed. 2013, 52, 2972–2976.
[13] D. J. Scherer, H. Sitzmann, G. Wolmershäuser, Angew. Chem. 1985, 97, 358–359; Angew. Chem. Int. Ed. Engl. 1985, 24, 351–353.
[14] M. Fleischmann, F. Dielmann, G. Balázs, M. Scheer, Chem. Eur. J. 2016, 22, 15248–15251.
[15] J. C. Gordon, V. T. Lee, R. Poli, Inorg. Chem. 1993, 32, 4460–4463.
[16] J. U. Desai, J. C. Gordon, H. Kraatz, V. T. Lee, B. E. Waltermire, R. Poli, A. L. Rheingold, C. B. White, Inorg. Chem. 1994, 33, 3752–3769.
[17] In the \(^1P^0\) NMR spectrum of the reaction solution, only one of the two signals of 4 could be detected, probably due to its low concentration, whereas the characteristic signal of its counterion \([\text{CP}^*\text{MoBr}_3]^+\) could be detected in the \(^3P^0\) NMR spectrum.
[18] Determined by \(^3P^0\) NMR spectroscopy (cf. Supporting Information).
[19] H. B. Kraatz, R. Poli, J. Organomet. Chem. 1994, 475, 167–175.
[20] Unfortunately, complex 12 could be obtained only once. All attempts to synthesize 12 in a targeted manner have failed so far.
[21] The use of a smaller number of equivalents of \(PCl_3\) (1, 2 or 3 equiv.) did not lead to an improvement of the chemoselectivity and often resulted in the crystallization of the residual 1, even though it was not detected in the \(^3P^0\) NMR spectrum. The use of a large excess of the halogenating agent (10 equiv.) led e.g. to the isolation of the known compound \([\text{CP}^*\text{MoCl}_3](\mu_3\text{Cl})\) in 14% crystalline yield, see Ref. [37].
[22] S. Alvarez, Dalton Trans. 2013, 42, 8617–8636.
[23] P. Pyykök, M. Atsumi, Chem. Eur. J. 2009, 15, 12770–12779.
[24] M. Baudler, J. Hellmann, Z. Anorg. Allg. Chem. 1982, 490, 11–18.
[25] P. L. Airey, Z. Naturforsch. 1969, 24b, 1393–1397.
[26] K. B. Dillon, A. W. G. Platt, T. C. Waddington, Inorg. Nucl. Chem. Lett. 1981, 17, 201–205.
[27] M. Piesch, S. Reichl, M. Seidl, G. Balázs, M. Scheer, Angew. Chem. Int. Ed. 2019, 58, 16563–16568.
[28] S. Heinl, G. Balázs, M. Scheer, Phosphorus, Sulfur, and Silicon and the Related Elements, 189, 2014, 1–9.
[29] O. J. Scherer, G. Schwarz, G. Wolmershäuser, Z. Anorg. Allg. Chem. 1996, 622, 951–957.
[30] V. A. Miluykov, O. G. Sinyashin, P. Lonnecke, E. Hey-Hawkins, Mendeleev Commun. 2003, 13, 212–213.
[31] D4-TPSSh(CPCM)/def2-TZVP level: a) D4: E. Caldeweyher, S. Ehlert, A. Hansen, H. Neugebauer, S. Spicher, C. Bannwarth, S. Grimme, J. Chem. Phys. 2019, 150, 154122; b) TPSSh: J. Tao, J. P. Perdew, V. N. Staroverov, G. E. Scuseria, Phys. Rev. Lett. 2003, 91, 146401; c) V. N. Staroverov, G. E. Scuseria, J. Tao, J. P. Perdew, J. Chem. Phys. 2003, 119, 12129–12137; d) Erratum: J. Chem. Phys. 2004, 121, 11507–11507; e) CPCM: J. Tomasi, B. Mennucci, R. Cammi, Chem. Rev. 2005, 105, 2999–3094; f) def2-TZVP: F. Weinigend, R. Ahlrichs, Phys. Chem. Chem. Phys. 2005, 7, 3297–3305.
[32] G. Knizia, J. Chem. Theory Comput. 2013, 9, 4834–4843.
[33] NBO 6.0. E. D. Glendening, J. K. Badenhoop, A. E. Reed, J. E. Carpenter, J. A. Bohmann, C. M. Morales, C. R. Landis, F. Weinhold (Theoretical Chemistry Institute, University of Wisconsin, Madison, WI, 2013); http://nbo6.chem.wisc.edu/.
[34] T. Lu, Q. Chen, Chemistry–Methods 2021, 1, 231–239.
[35] a) C. F.-W. L. Tian, Acta Phys. Chim. Sin. 2011, 27, 2786–2792; b) A. Savin, O. Jepsen, J. Flad, O. K. Andersen, H. Preuss, H. G. von Schnering, Angew. Chem. Int. Ed. Engl. 1992, 31, 187–188; c) A. D. Becke, K. E. Edgecombe, J. Chem. Phys. 1990, 92, 5397–5403.
[36] H. Jacobsen, Can. J. Chem. 2008, 86, 695–702.
[37] F. Abugideiri, G. A. Brewer, J. U. Desai, J. C. Gordon, R. Poli, Inorg. Chem. 1994, 33, 3745–3751.