Synthetic strategies to bicyclic tetraphosphanes using \(P_1\), \(P_2\) and \(P_4\) building blocks†

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Different reactions of Mes* substituted phosphanes (Mes* = 2,4,6-tri-tert-butylphenyl) led to the formation of the bicyclic tetraphosphane Mes*P4Mes* (5) and its unknown Lewis acid adduct 5GaCl3. In this context, the endo–exo isomer of 5 was fully characterized for the first time. The synthesis was achieved by reactions involving “self-assembly” of the \(P_1\) scaffold from \(P_2\) building blocks (i.e. primary phosphanes) or by reactions starting from \(P_2\) or \(P_4\) scaffolds (i.e. a diphosphene or cyclic tetraphosphane). Furthermore, interconversion between the exo–exo and endo–exo isomers were studied by \(^{31}P\) NMR spectroscopy. All compounds were fully characterized by experimental as well as computational methods.

Introduction

Ring systems composed of group 15 elements (pnictogens, \(P_n\)) are an intriguing and widely investigated aspect of main group chemistry.1–3 Within this field of research, the chemistry of phosphorus based ring systems has become an important branch of inorganic chemistry,4,5 especially in view of the fact that various phosphorus ring systems can be obtained by direct activation of white phosphorus.6–8 A lot of work has been carried out to improve the selectivity of these activation processes, involving functionalization of \(P_4\) by Lewis acids and bases, (transition) metals, radicals, or singlet carbenes such as N-heterocyclic carbenes (NHCs) or cyclic alkylaminocarbenes (CAACs).9–12

Among a plethora of structural motifs found in phosphorus ring systems, the simple tetraphosphabicyclo[1.1.0]butane (Scheme 1) is of special interest. Firstly, it can formally be derived from tetrahedral \(P_4\) by “simple” cleavage of one PP bond. Secondly, and more importantly, tetraphosphabicyclo[1.1.0]butanes were indeed obtained by \(P_4\) activation, thus representing worthwhile target molecules in phosphorus chemistry.

The first tetraphosphabicyclo[1.1.0]butane, (Me3Si)2N–P4–N(SiMe3)2 (1a, 1b, Scheme 2), was synthesized by the group of Niecke in 1982.13 It was derived from \(P_2\) building blocks utilizing PP coupling reactions. In the following years, some more examples emerged that were derived from \(P_2\) or \(P_3\) units, as reported by Cowley (2),4 Schmidpeter (3),14 Jutzi (4–6),16,19 Weber (5a),20 and Romanenko (5a).21 However, the majority of bicyclic tetraphosphanes was synthesized by \(P_4\) activation, the first example being exo–exo-Mes*P4Mes* (5a, Mes* = 2,4,6-tri-tert-butylphenyl), which was reported by Flick and co-workers in 1985.22,23 Improvement of \(P_4\) activation methods led to various other bicyclic \(P_4\) species, which can be categorized by the aforementioned types of \(P_4\) activation (Scheme 2); important contributions were made by the groups of Baudler (7, 8),24,25 Power (9–10),26,27 Krossing (11),28 Weigand (12–15)29,30 Tamm (16),31 Roessky and Stalke (17),32 Lappert (18),33 Masuda (19),34 Scheer (20, 21),10 Karaghiosoff (22),35 Lammertsma (23–25),12 and Jones (26).36 Additionally, various examples of transition metal complexes that incorporate bicyclic \(P_4\) scaffolds were reported.11,17–20 In contrast, very few examples of self-assembly reactions exist (i.e. the bicyclic \(P_4\) scaffold is built from \(P_1\) building blocks in a single reaction); literature reports include Wiberg’s (r-Bu)3Si–P–Si(r-Bu)3 (27)25 and Weigand’s [PnPh3–Pn–PnPh3]2 (28, Pn = As).41 Just recently, we reported on the cation [Mes*P4(Cl)Mes*]2 (29),45 which in itself was not derived by a self-assembly reaction, but its cyclic \(P_4\) precursor was.46

Scheme 1  Breaking one of the PP bonds in tetrahedral \(P_4\) formally yields the tetraphosphabicyclo[1.1.0]butane scaffold (A).
Interestingly, \( \textit{exo-exo} \)-substituted tetraphosphabicyclo[1.1.0]butanes are considerably more common than their \( \textit{endo-exo} \)-substituted counterparts, indicating that the latter are energetically less favoured. We therefore took interest in the synthesis and characterization of rare \( \textit{endo-exo} \)-substituted derivatives, which could be synthesized from \( \text{P}_1 \), \( \text{P}_2 \) and \( \text{P}_4 \) building blocks and were analysed by experimental and computational methods.

\section*{Results and discussion}

\subsection*{Synthesis and characterization of \( \textit{endo-exo-Mes}^*\text{P}_4\text{Mes}^* \) \( (5b) \)}

During our research in functionalized \( \text{cyclo} \)-tetraphosphabicyclic systems,\(^{16}\) we came across a publication of Romanenko \textit{et al.},\(^{21}\) wherein the authors described the synthesis of \( \textit{exo-exo-Mes}^*\text{P}_4\text{Mes}^* \) \( (5a) \) and the asymmetrically substituted bicyclic system \( \text{Mes}^*\text{P}_4\text{N}((i-Pr)_2) \) by reacting the diphosphene \( \text{Mes}^*\text{PPN}((i-Pr)_2) \) \( (30) \) with equimolar amounts of \( \text{HOTf} \) (Tf = SO\(_2\)CF\(_3\)). Intrigued by this curious method to synthesize bicyclic tetraphosphanes, we tried to reproduce the experiment described in the publication. However, fractional crystallization of the product mixture did not yield the reported compound \( \text{Mes}^*\text{P}_4\text{N}((i-Pr)_2) \), but rather \( \textit{endo-exo-Mes}^*\text{P}_4\text{Mes}^* \) \( (5b) \), alongside the known product \( 5a \) and minor amounts of the diphosphene \( \text{Mes}^*\text{PPMes}^* \) \( (31) \).\(^{17,48}\) Probably the available NMR and MS data were misinterpreted in the original publication. Compound \( 5b \) was now fully characterized for the first time, including NMR, Raman and IR spectroscopy, mass spectrometry, and single crystal X-ray diffraction.

\subsection*{Spectroscopic characterization}

Apart from minor impurities, the \( ^{31}\text{P} \) NMR spectrum of the reaction mixture showed an \( \text{A}_2\text{X}_2 \) \(( -273.2, -128.3 \text{ ppm}) \) and an \( \text{A}_4\text{MX} \) spin system \(( -220.4, -94.8, -54.7 \text{ ppm}) \) in a ratio of 1:4. The former set of signals was assigned to \( 5a \) (17\% yield based on \( ^{31}\text{P} \) NMR integrals), the latter to \( 5b \) (67\%); hence, the \( \textit{endo-exo} \)-isomer was actually formed in significant excess. The same NMR data were obtained for pure \( 5a \) and \( 5b \) (Fig. 1), which agree well with calculated NMR shifts and coupling constants (ESI) as well as previously reported NMR data.\(^{17,22}\) Moreover, both isomers could be nicely distinguished in the Raman spectrum due to different excitation energies of the vibrational “breathing” mode of the \( \text{P}_4 \) scaffold (Table 1). The corresponding Raman bands were easily identified as the most intense signals in both spectra (\( 5a: 592 \text{ cm}^{-1}, 5b: 568 \text{ cm}^{-1})\). The wavenumbers compare well to the symmetrical \( A_1 \) mode of tetrahedral \( \text{P}_4 \) in the gas phase (600 cm\(^{-1}\)).\(^{49}\) In case of \( 5b \), two distinct \( \text{P-C} \) valence modes were identified at 584 (\( \text{exo}\) ) and 591 cm\(^{-1}\) (\( \text{endo}\) ). In \( 5a \), the single \( \text{P-C} \) valence band was superimposed by the “breathing” mode of the bicyclic scaffold and could not be discerned.
Molecular structure

Crystallization from n-hexane yielded single crystals of 5b in the space group $P\bar{1}$ while crystallization from CH$_2$Cl$_2$ afforded crystals in the space group $P2_1/n$ (Fig. 2, right). The P–P and P–C bond lengths are similar in both modifications of 5b: the P1–P2 and P1–P3 bonds (av. 2.227, 2.233 Å) are close to the sum of the covalent radii ($\sum r_{cov} = 2.22$ Å),$^{50}$ whereas the P2–P4 and P3–P4 bonds (av. 2.213, 2.210 Å) as well as the transannular bond P2–P3 (av. 2.177 Å) are slightly shorter. This is in contrast to the structure of the previously reported exo-exo-isomer 5a (Fig. 2, left),$^{22}$ where all four peripheral P–P bonds exhibit similar lengths (av. 2.225 Å); the transannular bond, however, is likewise only 2.163(8) Å. The bond angles at the P atoms are all close to 60° and thus compare to tetrahedral P$_4$. Interestingly, the Mes$^*$ substituent in 5b is bent backwards above the P$_4$ scaffold, so the p-tert-butyl group rests on top of the exo-Mes$^*$ substituent, effectively shielding the top side of the bicyclic ring system. Hence, the fold angle of the butterfly-shaped P$_4$ scaffold is quite different in all three cases; it varies from 95.66(3)$^\circ$ (5a) across 105.75(5)$^\circ$ (triclinic 5b) to 107.78(3)$^\circ$ (monoclinic 5b), which can be attributed to Pauli repulsion between the endo-substituent and the opposite bridging atom (P1) in case of 5b as well as packing effects to account for the difference between the two modifications. A similar effect was observed in case of Ter$^P$Ter$^\prime$ (9a, 9b, Ter$^\prime$ = 2,6-bis(diisopropylphenyl)phenyl), where the difference between exo-exo (92.9$^\circ$) and endo-exo-isomer (108.1$^\circ$) is even larger.$^{27}$

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Table 1  Main vibrational modes of bicyclic tetraphosphanes in the Raman spectrum. Assignment of the symmetries based on approximate $C_{2v}$ symmetry of the P$_4$ scaffold

<table>
<thead>
<tr>
<th>Vibration mode</th>
<th>Description</th>
<th>Frequency [cm$^{-1}$]</th>
</tr>
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</table>
| ![Symmetrical valence breathing mode](image1) | Symmetrical valence “breathing mode” (A$_1$ mode, in phase) | 5a: 592  
5b: 568  
5a-GaCl$_3$: 597  
5b-GaCl$_3$: 567 |
| ![Peripheral bond stretch (B$_1$ mode)](image2)  | Peripheral bond stretch (B$_1$ mode)                      | 5a: 447  
5b: 500  
5a-GaCl$_3$: 497  
5b-GaCl$_3$: 518 |
| ![Transannular bond stretch (A$_1$ mode, out of phase)](image3) | Transannular bond stretch (A$_1$ mode, out of phase)     | 5a: 412  
5b: —  
5a-GaCl$_3$: 436  
5b-GaCl$_3$: — |
| ![Peripheral bond stretch (B$_2$ mode)](image4)  | Peripheral bond stretch (B$_2$ mode)                      | 5a: 412  
5b: 412  
5a-GaCl$_3$: 451  
5b-GaCl$_3$: 438 |
Computational study

Comprehensive DFT calculations were carried out to compare the isomers 5a and 5b. According to NBO analysis, the bonding situation is similar in both cases. The Wiberg and NLMO bond indices are near unity for all P–P bonds. However, due to the small bond angles, the electron density is not distributed symmetrically around the P–P bond axes, but rather bent outwards, resulting in banana-shaped bonds. This is illustrated by the electron localization function (ELF, Fig. 3 right), where the local maxima between the P atoms are found outside the lines of nuclear centres. Additionally, the symmetry and shape of the natural bond orbitals (NBOs) and molecular orbitals (MOs) support this picture.

Isomerization of 5b to 5a

At the PBE0/aug-cc-pVDZ level of theory, the exo–exo-isomer 5a is energetically favoured with respect to 5b by 10.4 kJ mol\(^{-1}\) (\(\Delta H_{298}^{\text{exo}}\)) or 8.80 kJ mol\(^{-1}\) (\(\Delta G_{298}^{\text{exo}}\)), respectively. These findings prompted us to investigate the thermodynamic equilibrium between both isomers: Indeed, when heating a THF solution of 5a and 5b (1:4 ratio) to 75 °C over a period of 50 days, slow conversion of 5b to 5a was observed in the \(\text{\textsuperscript{31}P}\) NMR spectrum. The forward and backward reaction were modelled as first order kinetics according to eqn (1).

\[
\frac{\text{d}[5b]}{\text{d}t} = -k_f[5b] + k_b[5a]
\]  

Hence, eqn (2) defines the reaction rate, [5a] and [5b] being the partial concentrations of 5a and 5b, respectively.

Using the synthetic protocol described above, 5a and 5b were always obtained in mixture. Separation was difficult and could only be achieved for small amounts of substance by repeated recrystallization. Designing a reaction that would yield 5b

\[
\Delta_G = -RT \ln K = -6.4(3) \text{ kJ mol}^{-1}
\]

Thus, the experimental Gibbs energy (at 75 °C) can be calculated:

\[
K = \frac{k_f}{k_b} = 9.3(1.4)
\]

Least-squares fitting of eqn (3) against the experimentally determined concentrations gave \(k_f = 2.77(11) \times 10^{-6} \text{ s}^{-1}\) and \(k_b = 0.30(3) \times 10^{-6} \text{ s}^{-1}\). Accordingly, the experimental equilibrium constant is:
Selective synthesis of \( \text{exo-\textit{exo}} \)-Mes*P\(_4\)Mes* (5a) by reduction

Concerning the synthesis of pure 5a, the isomerisation at elevated temperatures certainly offered a viable possibility to increase the isomeric ratio in favour of the \( \text{exo-\textit{exo}} \) isomer. Nevertheless, we found a much more straightforward way to synthesize pure 5a: starting from 32, reduction with stoichiometric amounts of Mg afforded 5a in high yields (based on \( ^{31}\text{P} \) NMR integrals: 95%; isolated substance: 73%) in a clean reaction (Scheme 5, top). For comparison, the original synthesis of 5a published by Fluck et al. afforded the bicyclic phosphane in a yield of only 5.2%.\(^{22}\) Formally, the reduction of 32 with Mg can be compared to the reduction of dichloro-\( \text{cyclo} \)-diphosphadiazanes, [\( \text{CIP}[\mu\text{-NR}]_2 \)], which results in the formation of \( \text{cyclo} \)-diphosphadiazanediyls, [\( \text{P}[\mu\text{-NR}]_2 \)], provided that the substituent R is bulky enough to prevent dimerization (Scheme 5, bottom).\(^{32}\) Yet, in contrast to the bicyclic tetraphosphane, the NP species comprise a planar ring system with singlet biradical character, as there is no classical bonding interaction between the transannular P atoms in this case.

**Synthesis of Mes*P\(_4\)Mes*–GaCl\(_3\) (5–GaCl\(_3\)) from P\(_3\) units**

When heating a solution of Mes*P(SiMe\(_3\))\(_2\) (34) in the presence of PCl\(_3\), a mixture of various products was obtained. Interestingly, the \( \text{exo-\textit{exo}} \)-isomer 5a was found to be one of the major products. Other species that could be identified were Mes*PPmes* (31), Mes*PCl\(_2\), P\(_3\), \( \text{endo-\textit{exo}} \)-isomer 5b (minor amounts), and some higher aggregates of uncertain composition. However, the reaction was rather slow, so we decided to add a Lewis acid for activation purposes. Indeed, in the presence of GaCl\(_3\), complete conversion was detected after one hour even at low temperatures (Scheme 6). Upon slow warming to ambient temperature, colourless crystals of 5a–GaCl\(_3\) or 5b–GaCl\(_3\) were obtained. Depending on the solvent, either one could be crystallized selectively, even though the ratio of both isomers in solution (7 : 5) remained unaffected by the choice of solvent.

**Spectroscopic characterization**

For both 5a–GaCl\(_3\) and 5b–GaCl\(_3\), an \( A_2MX \) spin system was expected due to unsymmetrical substitution of the bicyclic scaffold. Nonetheless, the room temperature \( ^{31}\text{P} \) NMR spectrum of 5a–GaCl\(_3\) only displayed two resonances (formal \( A_2X_2 \) pattern; \(-246.4, -97.1 \text{ ppm; Fig. 4} \)) which were shifted downfield by ca. 30 ppm with respect to non-coordinating 5a. At \(-80^\circ \text{C} \), though, the actual \( A_2MX \) spin system was resolved (\(-248.1, -114.0, -74.8 \text{ ppm} \)), with a rather large \( ^2J_{MX} \) coupling constant of +225 Hz (cf. 5b: \( ^2J_{MX} = -27 \text{ Hz} \)). To investigate the nature of this dynamic effect, temperature dependent NMR spectra were recorded. Basically, either an \textit{intramolecular} or an \textit{intermolecular} exchange (i.e. dissociation or bimolecular exchange) of the GaCl\(_3\) unit could be responsible for the observed line shapes, given that the concentration of free 5a is much lower than the concentration of the adduct 5a–GaCl\(_3\) (approx. ratio of \( 10^{-2} \) or less). However, at such low concentrations, the free phosphane could well be below the detection limit and it might not be discernible in the spectrum even at slow exchange. Accordingly, we added an excess of 5a, so the appearance of the NMR spectrum would change drastically if the free phosphane (i.e. dissociation) was involved in the
observed exchange.\textsuperscript{53} However, the signals of the excess phosphane could be detected independently of those of the adduct and the signal pattern of 5a-GaCl\textsubscript{3} remained unchanged, regardless of the excess of phosphane, proving an intramolecular mechanism (Scheme 7). Still, at higher temperatures above the coalescence of the M and X signal of 5a-GaCl\textsubscript{3}, slight broadening of the signals of free 5a was detected, hinting at an independent intermolecular exchange. Full lineshape analysis of the NMR signals (Fig. 4, ESI\textsuperscript{†}) facilitated derivation of the rate constants \(k\) at different temperatures. Using the Eyring eqn (7), the Gibbs energy of activation of the intramolecular exchange could be determined.

\[
k = \frac{k_B T}{h} \exp \left( \frac{\Delta G^\ddagger}{RT} \right)
\] (7)

Least-squares fitting gave a mean Gibbs energy of activation \(\Delta G^\ddagger = 39.5(4) \text{ kJ mol}^{-1}\), which compares, for example, to the activation barrier of the exchange of NH\textsubscript{3} in H\textsubscript{2}N-GaMe\textsubscript{3} (35.6 kJ mol\textsuperscript{-1}).\textsuperscript{54} According to the linearized Eyring plot, the enthalpy of activation \(\Delta H^\ddagger\) was found to be 39.5(4) kJ mol\textsuperscript{-1} and the entropy of activation \(\Delta S^\ddagger = -0.20(2) \text{ J mol}^{-1} \text{ K}^{-1}\), indicating a monomolecular transition state in agreement with the discussed intramolecular exchange reaction. The NMR data at slow exchange (\(-80 ^\circ\text{C}\)) correspond well with calculated NMR shifts and coupling constants (ESI\textsuperscript{†}).

The endo-exo isomer 5b-GaCl\textsubscript{3} showed an A\textsubscript{2}MX spin system (\(-224.5, -114.5, -50.0 \text{ ppm}\)), which resembled the NMR spectrum of free 5b. Like in 5a-GaCl\textsubscript{3}, the A part was broadened due to coupling with Ga. Owing to the arrangement of the Mes* substituents, no intramolecular exchange was observed; the linewidths did not change significantly upon cooling to \(-80 ^\circ\text{C}\). Nonetheless, upon addition of an excess of 5b the \(^{31}\text{P}\) NMR spectrum revealed a dynamic exchange free phosphane and adduct, which is most likely caused by a bimolecular exchange of the type 5-GaCl\textsubscript{3} + 5' = 5'-GaCl\textsubscript{3} + 5 (ESI\textsuperscript{†}).

Both isomers were nicely distinguishable in the solid state Raman spectra, due to the different positions of the “breathing mode” bands, similar to the non-coordinating tetraphosphabicyclo[1.1.0]butanes 5a and 5b. In contrast to the latter, the most intense Raman signal was caused by the Ga-Cl stretching at 343 (5a-GaCl\textsubscript{3}) or 348 cm\textsuperscript{-1} (5b-GaCl\textsubscript{3}). P-C valence modes could be identified at 613 (Mes* at coordinating P, 5a-GaCl\textsubscript{3}) and 618 cm\textsuperscript{-1} (endo-Mes*, 5b-GaCl\textsubscript{3}), the other ones were superimposed by the intense “breathing mode” signals. Important vibrational modes of the P\textsubscript{3} scaffold are summarized in Table 1.

**Molecular structure**

Lewis acid adduct 5a-GaCl\textsubscript{3} crystallized in the orthorhombic space group \(Pnma\) as \(n\)-hexane solvate (Fig. 5). The PP bond lengths lie within the range of typical single bonds, however the P3–P2 (or P3–P2') bond is slightly shortened (2.1805(9) Å); therefore, the bicyclic structure with two longer and two shorter bonds actually resembles the bicyclic scaffold in 5b.
The transannular bond (P2−P2′: 2.200(1) Å), on the other hand, is noticeably covalent radii (2.35 Å). The P3−Ga1 bond is somewhat elongated (2.4206(8) Å), most likely due to Pauli repulsion between the ortho-tet-butyl groups of the neighboring Mes* moiety and the GaCl3 unit. The bonding angles at the coordinating P atom (P3) are considerably flattened, so one of the Mes* substituents is bent further outwards. Moreover, the fold angle of the bicyclic system amounts to 98.69(3)° and is therefore 3° larger than in 5a.

Compound 5b-GaCl3 crystallized in the monoclinic space group P2_1/m either as toluene or CH2Cl2 solvate with similar cell parameters and molecular structure. Hence only the toluene solvate shall be discussed in the following: again, the bonds between the bridgehead atoms and the coordinating P atom (P2−P1 and P2′−P1: 2.1854(5) Å) are shortened in comparison with 5b, whereas the transannular bond is somewhat widened (P2−P2′: 2.2074(8) Å). The P−Ga bond length (2.3699(5) Å) is shorter than in 5a-GaCl3 and compares well to the sum of covalent radii. The angle of the P3−P2−P′ plane to the P3−C13 bond axis (96.92(6)°) is about 8° smaller than in 5b, so the Mes* substituent moves closer to the bicyclic scaffold. In contrast to 5a-GaCl3, the fold angle of 5b-GaCl3 lessens with respect to the free bicyclic tetraphosphane by 3° (102.64(2)°).

In both isomers, the substitution pattern at the bicyclic P scaffold is comparable to the borane adduct TerPMeMe-B(C_6F_5)_3 (23-B(C_6F_5)_3) or the bicyclic phosphino-phosphonium cation [Mes*P_4(Cl)Mes*]^+ (29).12,45

**Computational study**

NBO analysis revealed that the partial charges of the P atoms in 5a-GaCl3 and 5b-GaCl3 (bridgehead P: +0.10e, coordinating P: +0.24e, non-coordinating P: +0.31e) changed only slightly in comparison with 5a and 5b (bridgehead P: 0.00e, P(Mes*): +0.27e), implying a similar distribution of the electron density. Inspection of the molecular orbitals (MOs) showed that the principal bonding orbitals of the P4 scaffold remained intact. According to the electron localization function (ELF), the P−Ga bond is strongly polarized towards phosphorus (Fig. 6). The natural Lewis description actually suggests a non-bonding situation with a lone pair (LP) at phosphorus and an empty p-type orbital at Ga, with low P−Ga bond indices (NLMO: 0.34, Wiberg: 0.50). However, a second order perturbation analysis revealed a strong donor−acceptor interaction between the LP at P and the empty p-type orbital at Ga (5a-GaCl3: 530.5 kJ mol⁻¹, 5b-GaCl3: 555.2 kJ mol⁻¹); thus, the P−Ga bonding can be described as a classical dative bond. At the PBE0/aug-cc-pVDZ level of theory, the exo−exo isomer 5a-GaCl3 was calculated to be energetically favoured by 8.03 kJ mol⁻¹ (ΔG°(298)); therefore the energetic difference between exo−exo and endo−exo-isomer slightly decreased in comparison to non-coordinating 5a and 5b. This is reflected in the calculated Gibbs energies (ΔG°(298)) for the association of 5a or 5b and GaCl3, which amount to −46.7 kJ mol⁻¹ or −47.4 kJ mol⁻¹, respectively.

**Equilibrium between 5a-GaCl3 and 5b-GaCl3**

Similar to the free phosphanes, the GaCl3 adds 5a-GaCl3 and 5b-GaCl3 were found to interconvert slowly in solution at ambient temperature. Over a period of several weeks, the establishment of equilibrium was monitored by 31P NMR spectroscopy. Interestingly, the equilibrium constant was found to be 1.6(2), thus the amount of endo−exo isomer at equilibrium was significantly higher than in case of the free phosphanes. This is in agreement with the calculations, although the actual effect is even more pronounced. According to the experiment, the energetic difference between both isomers is just 1.24(4) kJ mol⁻¹ (ΔG).

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**Fig. 6** Exemplary description of the bonding in 5a-GaCl3. Left: Donor and acceptor NBOs describing the dative bond from P to Ga. Middle: P−Ga bond in the natural localized MO (NLMO) picture. Right: Electron localization function (ELF) depicted in a plane through atoms P1, P3 and Ga1. The P−Ga and Ga−Cl bonds are strongly polarized and exhibit partly ionic character. The deformation of the LP at P1 is due to Pauli repulsion with Cl2 and Cl2′ (out of plane).
Direct synthesis of Mes*P₄Mes*·GaCl₃ (5·GaCl₃)

As expected, 5a-GaCl₃ and 5b-GaCl₃ could be synthesized from pure 5a and 5b by treatment with equimolar amounts of GaCl₃. Mixing solutions of both reactants and subsequent evaporation of the solvent led to quantitative yield of the respective GaCl₃ adduct (Scheme 8). Due to the short reaction time (ca. 5 min), isomerization could be avoided.

Conclusions

We present new insights into the chemistry of tetraphosphabi-
cyclo[1.1.0]butanes: various synthetic approaches were investigated, involving precursor molecules with one, two or four phosphorus atoms. Thereby, the endo–exo isomer of Mes*P₄Mes* (5b) could be fully characterized for the first time and the interconversion of both isomers could by studied in detail. Furthermore, the hitherto unknown GaCl₃ adducts of both exo–exo and endo–exo isomer (5a-GaCl₃, 5b-GaCl₃) were thoroughly investigated, including experimental assessment of dynamic behaviour in solution and computational studies of the bonding situation.

Due to isomerization in solution, it is difficult to obtain either isomer purely; ideally, synthetic strategies should be designed to (a) minimize the reaction time and (b) take place at low temperatures to avoid thermodynamic equilibrium.

Experimental

All manipulations were carried out under oxygen- and moisture-free conditions under argon using standard Schlenk or Drybox techniques. All starting materials containing the Mes* moiety were synthesized according to modified literature procedures; other reactants and solvents were obtained from commercial sources and thoroughly dried. Detailed information concerning experimental procedures, data acquisition and processing, as well as purification of chemicals can be found in the ESI.†

Synthesis of 5a

A solution of [ClP(µ-PMes*)]₂ (206 mg, 0.30 mmol) in THF (3 mL) is added to magnesium turnings (10 mg, 0.42 mmol) and stirred at ambient temperature overnight. Subsequently, the solvent is removed in vacuo and the solid residue is extracted with n-hexane (5 mL). After filtration, the filtrate is concentrated and stored at 5 °C, resulting in crystallization of colourless exo–exo-Mes*P₄Mes*. Yield: 135 mg (0.22 mmol, 73%). CHN calc. (found) in %: C 70.34 (70.32), H 9.51 (9.35). 3¹P(H) NMR (CDCl₃, 121.5 MHz): δ = −273.2 Hz, 2 P, Pₜₙₜ, −177 Hz, 2 P, Pₜᵣᵢₚ, −128.3 Hz, 2 P, Pₚₚₚₚ. ¹H NMR (CDCl₃, 300.1 MHz): δ = 1.19 (s, 18 H, p-t-Bu), 1.63 (s, 36 H, o-t-Bu), 7.07 (m, 4 H, m-C₈H₈). Raman (633 nm, 15 s, 10 scans, cm⁻¹): ʋ = 3075 (1), 2963 (2), 2924 (2), 2903 (3), 2863 (1), 2777 (1), 2709 (1), 1588 (1), 1527 (1), 1473 (1), 1461 (1), 1442 (1), 1396 (1), 1365 (1), 1292 (1), 1281 (1), 1241 (1), 1208 (1), 1201 (1), 1175 (1), 1152 (1), 1128 (1), 1033 (2), 1020 (1), 931 (1), 891 (1), 822 (2), 775 (1), 637 (1), 592 (10), 563 (1), 490 (1), 475 (1), 463 (1), 447 (1), 432 (1), 412 (1), 387 (1), 351 (4), 294 (1), 259 (2), 211 (1), 191 (1), 177 (1), 136 (1), 125 (2), 107 (3), 86 (3).

Synthesis of 5b

Method 1: HOTf (180 mg, 1.12 mmol) is condensed onto a degassed solution of Mes*PPN(t-Pr)_2 (489 mg, 1.12 mmol) in CH₂Cl₂ (8 mL) at −196 °C. The reaction mixture is slowly warmed to ambient temperature overnight. The solvent is removed in vacuo and the residue is extracted with n-hexane (5 mL). Insoluble solids are filtered off. The clear orange filtrate is concentrated, resulting in crystallization of a mixture of exo–exo and endo–exo Mes*P₄Mes* (1:4 ratio). Yield: 120 mg (0.20 mmol, 35%). Re-crystallization yields pure endo-exo-Mes*P₄Mes*. Method 2: A mixture of [ClP(µ-PMes*)]₂ (835 mg, 1.22 mmol) and Me₄C₃N₂ (302 mg, 2.44 mmol) is dissolved in CH₂Cl₂ (10 mL) at 80 °C, resulting in a dark red solution. The reaction vessel is warmed to ambient temperature over a period of one hour, whereupon the solution is concentrated and stored at 5 °C, resulting in the crystallization of orange, block shaped crystals that were identified as Mes*PPMes*. The supernatant is separated and concentrated. Storage at 5 °C affords large colourless crystals of endo–exo-Mes*P₄Mes*. Yield: 105 mg (0.17 mmol, 14%). CHN calc. (found) in %: C 70.34 (70.32), H 9.51 (9.35). ³¹P(H) NMR (CDCl₃, 121.5 MHz): δ = −220.4 Hz, 2 P, Pₜₙₜ, −234 Hz, 2 P, Pₜᵣᵢₚ, −213 Hz, 2 P, Pₚₚₚₚ, −94.8 Hz, 2 P, Pₜᵣᵢₚ, −54.7 Hz, 2 P, Pₜᵣᵢₚ, −27 Hz, 1 P, Pₜᵣᵢₚ, −213 Hz, 2 P, Pₜᵣᵢₚ, −27 Hz, 1 P, Pₜᵣᵢₚ, −54.7 Hz, 2 P, Pₜᵣᵢₚ, −54.7 Hz, 2 P, Pₜᵣᵢₚ, −54.7 Hz, 2 P, Pₜᵣᵢₚ, −213 Hz, 2 P, Pₜᵣᵢₚ, −27 Hz, 1 P, Pₜᵣᵢₚ. ¹H NMR (CDCl₃, 300.1 MHz): δ = 1.19 (s, 9 H, p-t-Bu), 1.49 (s, 18 H, exo-Mes*, 6 H), 1.66 (m 18 H, m-C₈H₈), 7.02 (m, 2 H, exo-Mes*, 6 H), 7.05 (m, 2 H, endo-Mes*, 6 H). Raman (633 nm, 15 s, 20 scans, cm⁻¹): ʋ = 3168 (1), 3074 (1), 3055 (1), 2959 (4), 2924 (4), 2902 (5), 2865 (2), 2778 (1), 2712 (1), 1584 (3), 1520 (1), 1475 (1), 1466 (2), 1444 (2), 1399 (1), 1392 (1), 1360 (1), 1283 (2), 1251 (1), 1203 (1), 1186 (1), 1182 (1), 1173 (1), 1148 (1), 1132 (2), 1033 (3), 1017 (2), 932 (1), 919 (2), 897 (1), 877 (1), 822 (4), 772 (1), 744 (1), 740 (1), 647 (1), 638 (1), 591 (2), 584 (2), 568 (10), 500 (2), 490 (1), 473 (1), 435 (1), 419 (2), 412 (2), 381 (4), 363 (2), 330 (1),
Mes*P4Mes*·GaCl3. Yield: 30 mg (0.038 mmol, 67%). CHN

31P{1H} NMR (CD2Cl2, 121.5 MHz): δ = 246.4 (t, J(31P,31P) = −198 Hz, 2 P, Pbridgehead), −97.1 (broad, 2 P, PMes*). 31P{1H} NMR (CD2Cl2, 121.5 MHz, −80 °C): δ = −248.1 (dd, J(31P,31P) = −182 Hz, J(31P,1H) = −216 Hz, 2 P, Pbridgehead) = −114.0 (dt, J(31P,31P) = −182 Hz, J(31P,1H) = +225 Hz, 1 P, PMes*), −74.8 (dt, J(31P,31P) = −216 Hz, J(31P,1H) = +225 Hz, 1 P, P(Ga)Mes*). 1H NMR (CD2Cl2, 300.1 MHz): δ = 1.20 (s, 18 H, Mes*, p-t-Bu), 1.68 (s, 36 H, −Bu), 7.11 (t, J(1H,31P) = 5.0 Hz, 2 H, endo-Mes*, m-H), Raman (633 nm, 10 s, 4 scans, cm−1): ε = 3055 (2), 3035 (1), 2973 (5), 2966 (6), 2905 (7), 2886 (3), 2782 (1), 2714 (1), 1603 (1), 1582 (4), 1525 (1), 1463 (2), 1441 (2), 1394 (1), 1362 (1), 1284 (2), 1208 (2), 1173 (1), 1133 (2), 1029 (3), 1011 (2), 924 (1), 818 (3), 784 (2), 741 (2), 681 (3), 567 (7), 518 (1), 508 (1), 438 (3), 407 (2), 391 (2), 372 (2), 348 (10), 302 (1), 258 (3), 213 (1).

Detailed analytical data for all compounds, including low temperature NMR data, can be found in the ESI.†

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Notes and references