

PAPER

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[View Journal](#) | [View Issue](#)Cite this: *Dalton Trans.*, 2022, **51**, 8906Heterometathesis of diphosphanes (R_2P-PR_2) with dichalcogenides ($R'E-ER'$, $E = O, S, Se, Te$)†Callum Branfoot,^a Paul G. Pringle,^a *^a Natalie E. Pridmore,^a Tom A. Young^b and Duncan F. Wass^c

The reactions of R_2P-PR_2 with $R'E-ER'$, (where $E = Se, S, O, Te$) to give R_2P-ER' have been explored experimentally and computationally. The reaction of Ph_2P-PPh_2 with $PhSe-SePh$ gives $Ph_2P-SePh$ (**1**) rapidly and quantitatively. The $P-P/Se-Se$ reaction is inhibited by the addition of the radical scavenger TEMPO which is consistent with a radical mechanism for the heterometathesis reaction. Compound **1** has been fully characterised, including by X-ray crystallography. A range of other Ar_2P-SeR ($R = Ph, ^iBu$ or $CH_2CH_2CO_2H$) have also been prepared and characterised. The reaction of **1** with $[Mo(CO)_4(nbd)]$ ($nbd =$ norbornadiene) gives two products which, from their characteristic ^{31}P NMR data, have been identified as *cis*- $[Mo(CO)_4(Ph_2PSePh-P)_2]$ (**8**) and the mixed-donor complex *cis*- $[Mo(CO)_4(Ph_2P-SePh-P)(Ph_2P-SePh-Se)]$ (**9**). It is deduced that the P and Se atoms in ligand **1** have a comparable capacity to coordinate to Mo(0). The reaction of Ph_2P-PPh_2 with $PhS-SPh$ gives Ph_2P-SPh (**2**) quantitatively but no reaction was observed between Ph_2P-PPh_2 and $PhTe-TePh$. Heterometathesis between Ph_2P-PPh_2 and $^tBuO-O^tBu$ does not occur thermally but has been observed under UV irradiation to give Ph_2P-O^tBu along with P(V) oxidation by-products. DFT calculations have been carried out to illuminate why heterometatheses with dichalcogenides $R'E-ER'$ occur readily when $E = S$ and Se but not when $E = O$ and Te . The calculations show that heterometathesis is predicted to be thermodynamically favourable for $E = O, S$ and Se and unfavourable for $E = Te$. The fact that a metathesis reaction between Ph_2P-PPh_2 with $^tBuO-O^tBu$ is not observed in the absence of UV radiation, is therefore due to kinetics.

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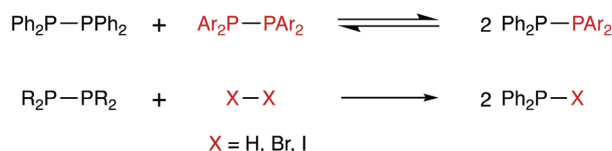
Introduction

The chemistry of diphosphanes (R_2P-PR_2) has attracted considerable attention, and the high reactivity of the P-P bond has been exploited for the diphosphination of a wide range of unsaturated substrates, including alkenes,^{1–4} alkynes,^{4–8} 1,3-dienes,⁹ arynes,¹⁰ CO_2 and CS_2 .¹¹ We recently reported that tetra-aryldiphosphanes readily undergo homometathesis reactions (Scheme 1) under ambient conditions, most likely *via* homolysis of the P-P bond and the generation of $Ar_2P^{\cdot}$ radicals.¹² Also shown in Scheme 1 are diphosphane reactions with diatomic X_2 that could be classed as examples of diphosphane heterometathesis reactions.^{13,14}

Here, we report our experimental and computational investigations of the heterometatheses shown in Scheme 2¹⁵

and show that this is an effective route for the synthesis of compounds of the type Ph_2P-SeR .

Compounds containing P-S or P-Se bonds have been widely applied in organic synthesis as reagents for S or Se transfer (Lawesson's reagent¹⁶ and Woollins' reagent¹⁷ respectively). Furthermore, P/S and P/Se compounds are of interest in their own right^{18–20} with potential applications ranging from semi-conductors to pesticides.²¹ However, to date, little attention has been given to compounds of the type R_2P-SR or R_2P-SeR which are amongst the simplest organophosphorus(III) compounds containing S or Se. Arbuzov reported the first examples of Ph_2P-SR ($R =$ alkyl) compounds over a century ago.²² In the 1960s, McLean reported the synthesis of $Ph_2P-SePh$ (**1**) and Ph_2P-SPh (**2**) from Ph_2PCl by the routes shown in

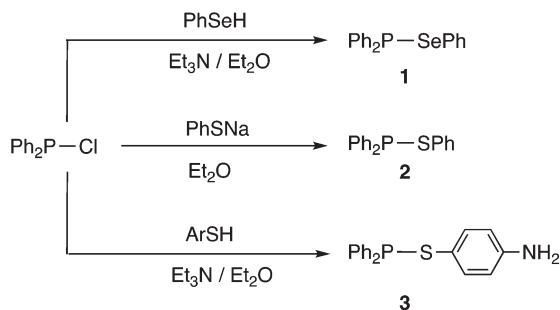


Scheme 1 Metathesis reactions of diphosphanes.

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E-mail: paul.pringle@bristol.ac.uk^bChemistry Research Laboratory, University of Oxford, Oxford OX1 3TA, UK^cCardiff Catalysis Institute, School of Chemistry, Cardiff University, Cardiff CF10 3AT, UK† Electronic supplementary information (ESI) available. CCDC 2162103. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d2dt01093c>



Scheme 2

Scheme 3 Previously reported $\text{Ar}_2\text{P}-\text{ER}$ compounds.^{23,24}

Scheme 3, although no NMR spectroscopic data for these compounds were reported.²³ More recently, Cui *et al.*²⁴ prepared thioaniline derivative **3** similarly (Scheme 3).

Results and discussion

Diphosphane–diselenide metathesis

The reaction between equimolar quantities of tetraphenyldiphosphane and diphenyldiselenide in THF (Scheme 4) was monitored by $^{31}\text{P}\{^1\text{H}\}$ NMR spectroscopy. After 10 min, the signal for $\text{Ph}_2\text{P}-\text{PPh}_2$ at $\delta(\text{P}) -15.0$ ppm had been replaced by a singlet at $\delta(\text{P}) +29.4$ ppm with ^{77}Se satellites ($^1J_{\text{PSe}} = 229$ Hz); the $^{77}\text{Se}\{^1\text{H}\}$ NMR spectrum is a doublet at $\delta(\text{Se}) 307.5$ ppm ($^1J_{\text{PSe}} = 229$ Hz), consistent with the formation of the selanylphosphane, $\text{Ph}_2\text{P}-\text{SePh}$ (**1**). The product was isolated in 92% yield and further characterised by ^1H and $^{13}\text{C}\{^1\text{H}\}$ NMR, and

mass spectrometry (see ESI† for the data).²⁵ Crystals of **1** were grown from $\text{CH}_2\text{Cl}_2/n$ -hexane *via* vapour diffusion and its X-ray crystal structure determined (see Fig. 1).

The P–Se bond length in **1** of 2.2620(5) Å is close to the mean average of 2.217 Å obtained from the 686 single crystal X-ray structures that feature a P–Se bond in the Cambridge Structural Database (CSD). There are no crystal structures in the CSD of compounds of the type $\text{Ar}_2\text{P}-\text{SeAr}'$ (or $\text{Ar}_2\text{P}-\text{SAr}'$) with which to compare **1**, but the pyramidal geometry at P and bent geometry at Se are as expected.

The $\text{P}_2\text{R}_4/\text{Se}_2\text{R}_2$ heterometathesis reaction has been extended to the preparation of the new selanylphosphanes **4–7** (Scheme 4) by combination of the appropriate diphosphane and diselenide. Each of these compounds was isolated in good yield (quantitative yields observed by *in situ* $^{31}\text{P}\{^1\text{H}\}$ NMR spectroscopy) as an oil or oily solid and then fully characterised by $^{31}\text{P}\{^1\text{H}\}$, $^{77}\text{Se}\{^1\text{H}\}$, ^1H , $^{13}\text{C}\{^1\text{H}\}$ and APCI mass spectrometry (see ESI† for the data). The modest isolated yields of **4** and **7**

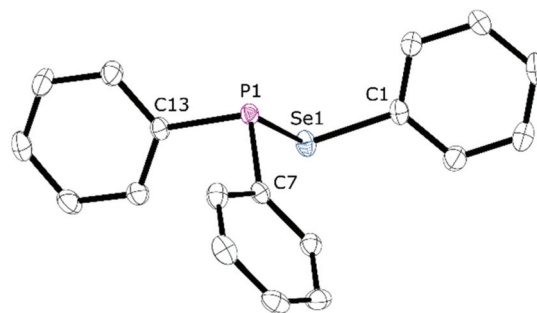
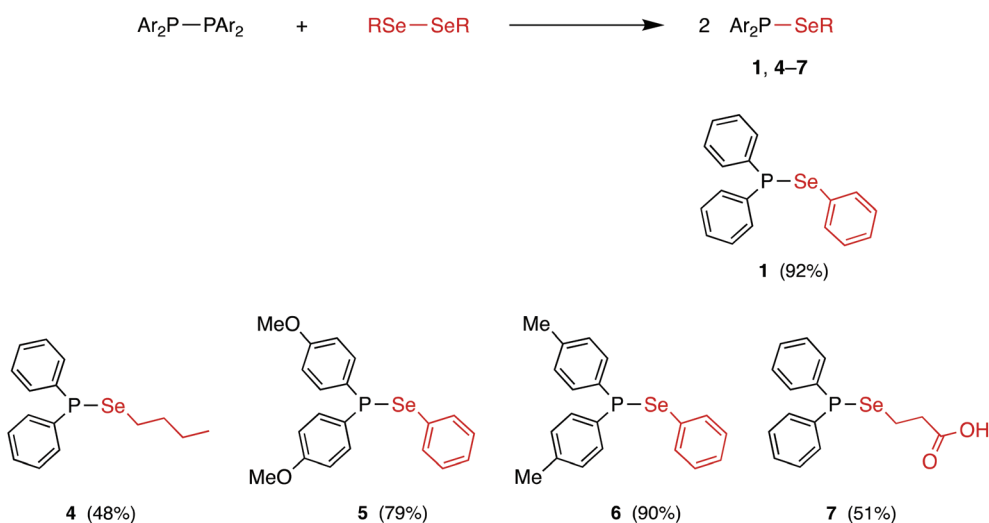


Fig. 1 Thermal ellipsoid (50% probability) representation of the crystal structure of diphenyl(phenylselanyl)phosphane (**1**), hydrogen atoms omitted for clarity. Selected bond lengths (Å) and bond angles (°): P1–Se1 2.2620(5), P1–C7 1.8421(18), P1–C13 1.8343(18), Se1–C1 1.9316(18); C7–P1–Se1 103.62(6), C7–P1–C13 100.15(8), C13–P1–Se1 96.38(6), P1–Se1–C1 98.66(5).



Scheme 4



(shown in Scheme 4) are due to losses during work-up, since the NMR yields were quantitative. These reactions were carried out in THF, CH₂Cl₂ or toluene and in no case was the solvent observed to affect the rate or outcome of the reaction, which in all cases had proceeded to completion within the time required (*ca.* 30 s) to obtain a ³¹P{¹H} NMR spectrum of the reaction mixture. Of particular note is the carboxylic acid 7, which shows that the P–Se bond is tolerant of reactive functional groups. The synthesis of **1** in CDCl₃ was repeated in an amberised NMR tube (to reduce the effect of photolysis) but again, complete conversion to **1** was observed within 30 s.

When the reaction of Ph₂P–PPh₂ with PhSe–SePh was carried out in the presence of 4 equiv. of TEMPO in THF, the heterometathesis reaction was inhibited: in the absence of TEMPO, complete conversion was observed within 1 min, while in the presence of TEMPO, the reaction proceeded to 54% conversion after 90 min. Other products are detected associated with the formation of Ph₂P–TEMPO species (see ESI†). This is consistent with radicals being involved in the reaction, as we previously demonstrated in the homometathesis of diphosphanes.¹² As a result, the radical chain mechanism shown in Scheme 5 is proposed. Diselenides are well-known to form RSe• radicals by photolytic cleavage of the weak Se–Se bond (BDE 41 kcal mol^{−1}).^{26–32} It is therefore plausible that RSe–SeR cleavage to produce RSe• radicals initiates the radical chain process shown in Scheme 5.³³

McLean reported²³ that Ph₂P–SePh (**1**) is unstable with respect to isomerisation to Ph₃P=Se at 100 °C, over a period of 3–4 h. We have found that **1** is relatively stable under ambient conditions, which makes it easy to handle. Thus solid samples of **1** can be stored under argon at room temperature with <10% degradation observed (traces of Ph₂PH detected) even after 4 months. When water was added to a solution of **1**

in CDCl₃ and the emulsion shaken under nitrogen, only very slow hydrolysis to Ph₂P(O)H was observed: after 2 days, the hydrolysis mixture contained unreacted **1** (*ca.* 60%) along with a prominent signal (22%) at +32.5 ppm, consistent with the formation of Ph₂P(O)OH;³⁴ crystals that grew from this solution were shown to match the structure of Ph₂P(O)OH, ‘DPPHIN’ in the CSD.

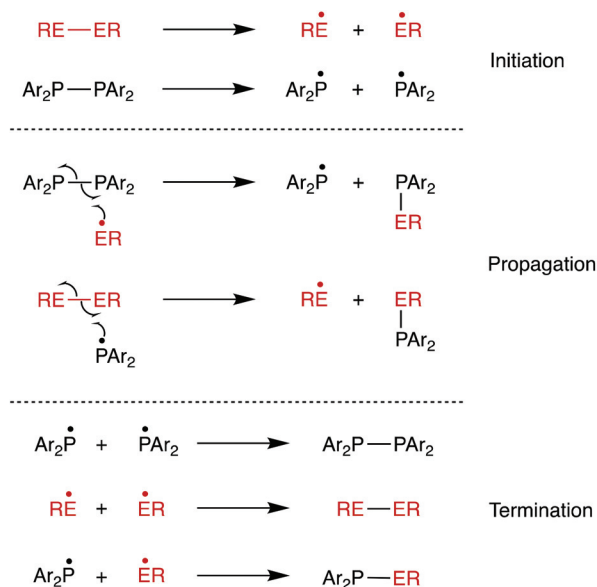
The observed kinetic stability of selanylphosphane **1** prompted us to explore its coordination chemistry with Mo(0). To the best of our knowledge, selanylphosphanes have not previously been used as ligands for transition metals. It was of interest to investigate which of the two potential donor atoms (P and Se) would bind to the metal in the complexes, since both are known to bind to metals in mixed P₂Se ligands such as Ph₂PCH₂CH₂SePh.^{35–37} Treatment of [Mo(CO)₄(nbd)] (nbd = norbornadiene) with 2 equiv. of **1** in CD₂Cl₂, gave a mixture of two products in the ratio of *ca.* 4 : 1 according to ³¹P{¹H} NMR spectroscopy (see Fig. 2), which have been assigned to the isomers of *cis*-[Mo(CO)₄(**1**)₂] (**8** and **9** in Scheme 6) on the basis of their characteristic ³¹P NMR parameters.

The major product is a singlet at δ(P) +59.7 ppm with outer ⁷⁷Se satellites (¹J_{PSe} = 333 Hz) that are themselves split into doublets (²J_{PP} = 25 Hz) and inner ⁷⁷Se satellites (³J_{PSe} = 40 Hz). This product is assigned the structure **8** where both ligands are P-bound *cis* on the Mo; this is supported by the large coordination chemical shift (Δδ_P = +29.2) and the small ²J_{PP}. The inequivalence observed in the satellites is a result of the loss of symmetry in the ⁷⁷Se isotopologue (see Fig. 2).

The second product is assigned structure **9**, containing one P-bound and one Se-bound ligand **1**, on the basis of the ³¹P NMR data. Two doublets are observed at δ(P¹) +62.4 ppm and δ(P²) +17.8 ppm (³J_{PP} = 22 Hz). The Δδ_P of +31.2 for P¹ in **9** is similar to the Δδ_P of the P in **8** and is therefore consistent with P¹ being directly bound to Mo. The Δδ_P of −12.7 ppm for P² is assigned to the Se-bound ligand in **9**. After the mixture of products was heated to 60 °C in CDCl₃ for 3.5 h, complex **9** was the dominant species (ratio of complexes **9** : **8** was 5 : 1 according to ³¹P NMR spectroscopy, see ESI†). In the IR spectrum of the mixtures of **8** and **9**, several absorptions in the range 1892–2027 cm^{−1} were evident, as expected for the ν(CO) bands for these *cis* complexes present. Solutions of the molybdenum complexes **8** and **9** in a CH₂Cl₂/water emulsion did not undergo any changes after 17 h, indicating good water tolerance.

The analogous complexation reaction of selanylphosphane **7** with [Mo(CO)₄(nbd)] in CH₂Cl₂ produced a similar pattern of products according to ³¹P NMR spectroscopy (see ESI†): two products in the ratio 4 : 1, with a singlet at +50.8 ppm (with ⁷⁷Se satellites) and two doublets at +54.0 and 17.7 ppm (³J_{PP} = 21 Hz) consistent with the formation of analogues of **8** and **9**.

The notable conclusion from the Mo coordination chemistry is that, for Ph₂P–SeR, the PPh₂ and SeR groups have comparable donor ability. The fine balance between the linkage isomers with P or Se coordination is likely a consequence of the donor atoms both being soft and the steric hindrance around the SeR being less than around the PPh₂.



Scheme 5 Radical chain mechanism proposed for diphosphane–dichalcogenide metathesis.



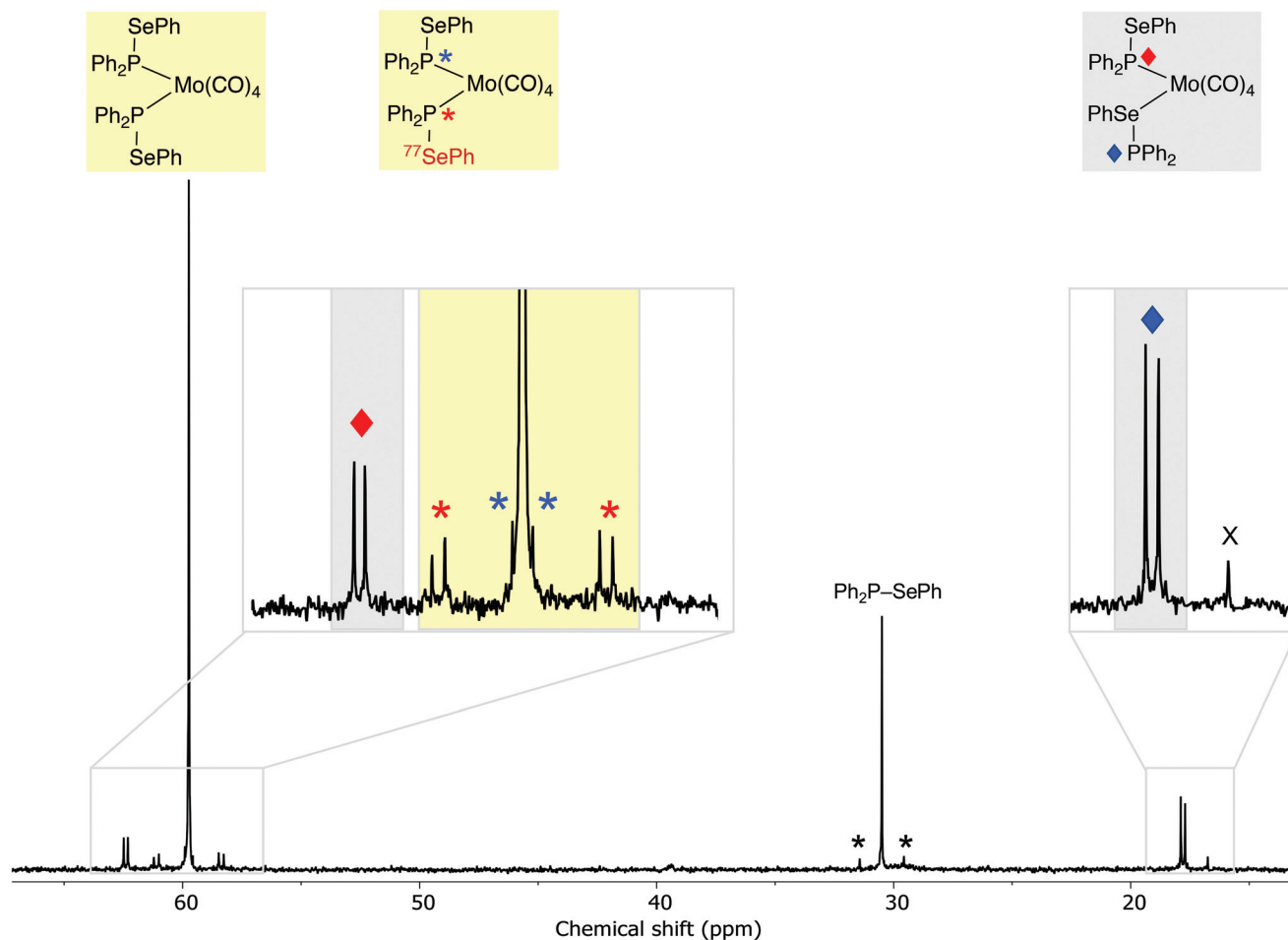
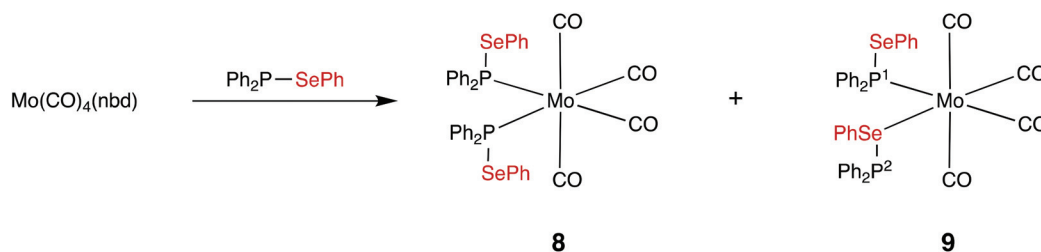


Fig. 2 $^{31}\text{P}\{^1\text{H}\}$ NMR spectrum of the product mixture obtained from the reaction of $\text{Ph}_2\text{P}-\text{SePh}$ with $[\text{Mo}(\text{CO})_4(\text{nbd})]$. The large singlet at ca. 60 ppm is assigned to the symmetrical P,P-complex **8** and the expansion shows the signals associated with the ^{77}Se isotopologue of **8**, which show satellite signals due to $^1J_{\text{PSe}}$ (*) and $^3J_{\text{PSe}}$ (*). The doublets at ca. +62 (◆) and +18 (◆) are assigned to **9**, the P,Se-linkage isomer of **8** (^{77}Se satellites obscured by the noise). The signal at ca. 31 ppm is for unreacted ligand **1** with ^{77}Se satellites (*). The minor signal labelled X at ca. +17 ppm is unassigned.



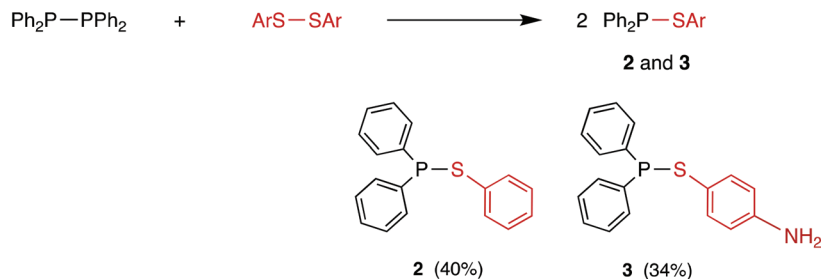
Scheme 6

Diphosphane–disulfide metathesis

The reaction of tetraphenyldiphosphane with diphenyl disulfide or 4-aminophenyl disulfide gave the previously reported sulfanyldiphosphanes **2** and **3** respectively (see Scheme 7).^{23,24,38} Compared with the rapid diselenide reactions (Scheme 4), the disulfide analogues are sluggish, requir-

ing up to 20 h to reach completion in an unagitated NMR tube. The reactions were significantly more rapid when they were stirred and were most rapid in chloroform (as with the diphosphane homometathesis).¹² The conversions to **2** and **3** were apparently quantitative in the reactions monitored by $^{31}\text{P}\{^1\text{H}\}$ NMR spectroscopy but the isolated yields were modest (see Scheme 7); there were significant losses on the





Scheme 7

short alumina column used to purify the crude products (see ESI†).

The diphosphane–disulfide metathesis was inhibited by the presence of TEMPO (4 equiv.), consistent with the reaction following the radical chain mechanism shown in Scheme 5, as for the diphosphane–diselenide process. The reaction of $\text{Ph}_2\text{P}-\text{PPh}_2$ with $\text{PhS}-\text{SPh}$ in CDCl_3 was followed by $^{31}\text{P}\{^1\text{H}\}$ NMR spectroscopy and **2** was formed in 34% yield after 1 h of reaction. When the same reaction was performed in the presence of 4 equivalents of TEMPO, 8% conversion to **2** was observed after 1 h (see ESI†). The higher rate observed with the diselenide than with the disulfide reflects the ease with which homolysis of the weak Se–Se bond takes place compared to the homolysis of either the S–S or P–P bonds.^{39–41}

Attempted diphosphane–ditelluride and diphosphane–peroxide metatheses

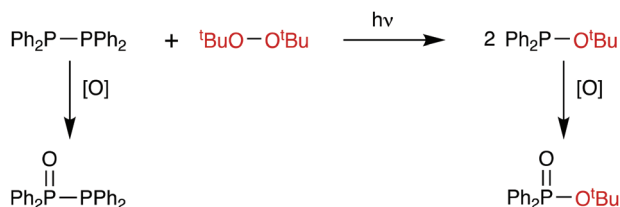
When $\text{Ph}_2\text{P}-\text{PPh}_2$ and $\text{PhTe}-\text{TePh}$ were mixed in C_6D_6 , no heterometathesis reaction (Scheme 2) was observed even after 12 days. The compound $\text{Ph}_2\text{P}-\text{TePh}$ has not been previously reported, although its P(v) isomer $\text{Ph}_3\text{P}=\text{Te}$ is readily prepared.⁴²

Similarly, when $\text{Ph}_2\text{P}-\text{PPh}_2$ and $t\text{BuO}-\text{O}t\text{Bu}$ were mixed in toluene, no heterometathesis reaction (Scheme 8) to give the known¹⁷ compound $\text{Ph}_2\text{P}-\text{O}t\text{Bu}$ was observed after 72 h. The only products detected by $^{31}\text{P}\{^1\text{H}\}$ NMR spectroscopy were the monoxide $\text{Ph}_2\text{P}(\text{O})-\text{PPh}_2$ (12%: 2 doublets at +32.7 and –24.7, $J_{\text{PP}} = 218 \text{ Hz}$)⁴³ and Ph_2PH (12%, –40.2 ppm).¹² Even when a large excess (~15-fold) of $t\text{BuO}-\text{O}t\text{Bu}$ was used and the reaction mixture was heated to 60 °C, only oxidation products were observed and no heterometathesis product. However, when this reaction was repeated in C_6D_6 and irradiated with near-UV

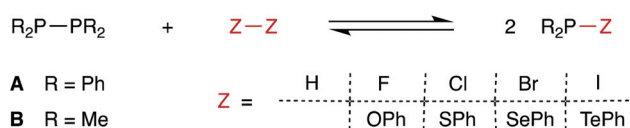
light, gradual formation of a new species was observed by $^{31}\text{P}\{^1\text{H}\}$ NMR spectroscopy characterised by a singlet at +87.1 ppm and assigned to the phosphinite $\text{Ph}_2\text{P}-\text{O}t\text{Bu}$ on the basis of the chemical shift being consistent with the reported value.⁴⁴ After the irradiation was continued for a further 1 h, a significant quantity of the phosphinate $\text{Ph}_2\text{P}(\text{O})-\text{O}t\text{Bu}$ (47% of the total ^{31}P integral, see ESI†) was identified by a singlet at +25.7 ppm, in good agreement with literature data.⁴⁵ The formation of this P(v) species was further supported by the detection of the phosphinate $[\text{M} + \text{Na}]^+$ ion by mass spectrometry (297.1 m/z observed, 297.1 theoretical). In summary, there is evidence that under UV irradiation, the diphosphane/peroxide heterometathesis does indeed occur but that by-products associated with oxidation by $t\text{BuO}-\text{O}t\text{Bu}$ contaminate the product (see Scheme 8).

DFT study of heterometathesis reactions of diphosphanes

The general reaction that has been calculated is shown in Scheme 9 and the results are given in Table 1. It was anticipated that the results for the diphosphane metatheses with diatomic molecules Z_2 would be the simplest to interpret. The DFT-calculated ΔE values for the addition of diatomic Z_2 to $\text{R}_2\text{P}-\text{PR}_2$, where $\text{R} = \text{Ph}$ (A), or Me (B), are presented as entries 1–10 of Table 1. The values of ΔH estimated using the mean bond strengths for P–P (51 kcal mol^{–1}),⁴⁶ Z–Z, and P–Z are also given in Table 1 and there is good agreement between ΔE and ΔH for $\text{Z} = \text{H}, \text{F}, \text{Cl}, \text{Br}$ and I . The two consistent trends in the heterometathesis equilibria are: (i) ΔE becomes increasingly more favourable with increasing electronegativity of Z ; (ii) $\text{Me}_2\text{P}-\text{PMe}_2$ metatheses are more favourable (by 6–10 kcal mol^{–1}) than the corresponding $\text{Ph}_2\text{P}-\text{PPh}_2$ metatheses. The position of the equilibrium in Scheme 9 is determined by the relative Z–Z and P–Z bond energies, which in turn will be influenced by a combination of the following factors. (a) The very high H–H and very low F–F bond strengths dominate the



Scheme 8



Scheme 9



Acknowledgements

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- (a) The heterometathesis reaction between Ph₂Bi–BiPh₂ and PhE–EPh (E = S, Se, Te) to give Ph₂Bi–EPh has been previously reported, see: F. Calderazzo, A. Morvillo, G. Pelizzi, R. Poli and F. Ungari, Reactivity of Molecules Containing Element–Element Bonds. 1. Nontransition Elements, *Inorg. Chem.*, 1988, **27**, 3730–3733; (b) The reaction between Me₂P–PMe₂ and MeE–EME produces equilibrium mixtures with the corresponding Me₂P–EME (E = S, Se, Te); see: A. J. Ashe III and E. G. Ludwig Jr., The Exchange Reactions of Tetramethylpnictogens with Dimethyldichalcogenides, *J. Organomet. Chem.*, 1986, **308**, 289–296.
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