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Author(s): Robertson, Stuart; Chivers, Tristram; Tuononen, Heikki

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Experimental and Theoretical Investigations of the Redox Behavior of the Heterodichalcogenido Ligands [(EPr₂TePr₂)N](E = S, Se): Cyclic Cations and Acyclic Dichalcogenide Dimers

Stuart D. Robertson †, Tristram Chivers *, † and Heikki M. Tuononen ‡

Department of Chemistry, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada, T2N 1N4 and Department of Chemistry, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland.

* To whom correspondence should be addressed.
Telephone: (403) 220-5741
Fax: (403) 289-9488
E-mail: chivers@ucalgary.ca

† University of Calgary
‡ University of Jyväskylä
The two-electron oxidation of the lithium salts of the heterodichalcogenidoimidodiphosphinate anions [(EP<sub>i</sub>Pr<sub>2</sub>(TeP<sub>i</sub>Pr<sub>2</sub>)N]<sup>-</sup> (1a, E = S; 1b, E = Se) with iodine yields cyclic cations [(EP<sub>i</sub>Pr<sub>2</sub>(TeP<sub>i</sub>Pr<sub>2</sub>)N]<sup>+</sup> as their iodide salts [(SP<sub>i</sub>Pr<sub>2</sub>(TeP<sub>i</sub>Pr<sub>2</sub>)N]I (2a) and [(SeP<sub>i</sub>Pr<sub>2</sub>(TeP<sub>i</sub>Pr<sub>2</sub>)N]I (2b). The five-membered rings in 2a and 2b both display an elongated chalcogen-tellurium bond as a consequence of an interaction between tellurium and the iodide anion. One-electron reduction of 2a and 2b with cobaltocene produces the neutral dimers (EP<sub>i</sub>Pr<sub>2</sub>NP<sub>i</sub>Pr<sub>2</sub>Te-)<sub>2</sub> (3a, E = S; 3b, E = Se), which are connected exclusively through a tellurium-tellurium bond. Two-electron reduction of 2a and 2b with two equivalents of cobaltocene regenerates the corresponding dichalcogenidoimidodiphosphinate anions as ion-separated cobaltocenium salts Cp<sub>2</sub>Co[(EP<sub>i</sub>Pr<sub>2</sub>(TeP<sub>i</sub>Pr<sub>2</sub>)N] (4a, E = S; 4b, E = Se). The ditellurido analogue Cp<sub>2</sub>Co[(TeP<sub>i</sub>Pr<sub>2</sub>)<sub>2</sub>N] (4c) has been prepared in the same manner for comparison. Density functional theory calculations reveal that the preferential interaction of the iodide anion with tellurium is determined by the polarization of the LUMO [σ*(E-Te)] of the cations in 2a and 2b towards tellurium and that the formation of the dimers 3a and 3b with a central Te-Te linkage is energetically more favorable than the structural isomers with either E-Te or E-E bonds. Compounds 2a, 2b, 3a, 3b, 4a, 4b and 4c have been characterized in solution by multinuclear NMR spectroscopy and in the solid state by X-ray crystallography.
Introduction

The chemistry of the dichalcogenidoimidodiphosphinates (I) has been studied comprehensively since the 1960s.\textsuperscript{1} Such compounds are of great interest as they represent inorganic analogues of the common organic chelating ligand acetylacetonate (acac), although the inorganic backbone displays much greater flexibility than the organic counterpart whose planarity is imposed by an array of sp\textsuperscript{2}-hybridized centers. A considerable variety of different dichalcogenidoimidodiphosphinates are known as a consequence of changing the chalcogens and/or the organic groups bound to phosphorus. The extensive number of O, S and Se-containing derivatives and their complexation chemistry with a number of main group and transition metals have been comprehensively reviewed.\textsuperscript{2-4} Several of these homoleptic metal complexes were shown by O’Brien et al. to be suitable single-source precursors for the generation of semiconducting thin films\textsuperscript{5-12} or quantum dots\textsuperscript{13} of metal selenides via chemical vapor deposition processes. After a brief hiatus, interest in this class of ligand was reinvigorated by the discovery of the first tellurium-containing examples, which were obtained as alkali metal salts (I, E = Te; R = Ph,\textsuperscript{14} iPr\textsuperscript{15}). The coordination chemistry of the ditellurido ligand\textsuperscript{15} was propelled by the discovery of some alternative bonding modes with respect to the lighter chalcogen derivatives.\textsuperscript{16-18} In addition, semiconducting thin films of a variety of metal tellurides were generated by using homoleptic complexes as single-source precursors.\textsuperscript{19-21}
Subsequently, a comprehensive study of the redox chemistry of the dichalcogenidoimidodiphosphinate system was carried out, which resulted in the completion of the sequence of different oxidation states (-1/0/+1). The cationic derivatives were synthesized as iodide salts [(EPPr₂)₂N]I (2, E = Se, Te) by the two-electron oxidation of the corresponding anions with iodine. These five-membered, 6 π-electron rings were found to be considerably puckered, in contrast to chalcogen-nitrogen cations such as [E₃N₂]²⁺ (E = S, Se) and [S₂N₃]⁺, which are planar. A structural analysis revealed that these novel ring systems contain elongated chalcogen-chalcogen bonds. On the basis of density functional theory (DFT) calculations the elongation was attributed to donation of electron density from a lone pair on the iodide anion into the Te-Te σ⁺ orbital (LUMO) of the cation. Such lengthening of the chalcogen-chalcogen bond was not evident in ion-separated salts prepared by exchanging I⁻ for SbF₆⁻.
Furthermore, one-electron oxidation of the anions in 1 (E = S, Se, Te) generated neutral dimers (3, R = iPr, E = Se, Te; R = iBu, E = S, Se),\textsuperscript{27} formally involving the association of two \([E^iPr_2PN^iPr_2PE]\) radicals through E-E bonds that are elongated with respect to those in the corresponding organic dichalcogenides PhEEPh.\textsuperscript{28-30} Calculations showed that the SOMO of the radicals \([TeR_2PNR_2PTe]\) is based on the two tellurium centers and involves a linear combination of tellurium p-orbitals.\textsuperscript{22} The calculated energy of dimerization for the methyl-substituted tellurium radical was \(-80\) kJ mol\(^{-1}\), cf. \(D(\text{Te-Te}) = 138\) kJ mol\(^{-1}\) in PhTeTePh, consistent with a significantly weakened Te-Te bonding interaction in 3 (E = Te).

Recently, we described the synthesis of the first heterodichalcogenidoimidodiphosphinate ligands containing tellurium \([\{(EP^iPr_2)(TeP^iPr_2)N\}] (E = S, Se, Te) as their TMEDA-solvated lithium derivatives.\textsuperscript{31} In this paper we report the results of the investigations of the oxidation of these mixed chalcogen anions with iodine in order to determine (a) the effect of this asymmetry on the cation-iodide interaction of the resulting species \([\{(EP^iPr_2)(TeP^iPr_2)N\}]I (E = S, Se) and (b) the preferred chalcogen-chalcogen interaction in the neutral dimers \((EP^iPr_2NP^iPr_2Te)_2 (E = S, Se, Te). A series of ion-separated salts, \(\text{Cp}_2\text{Co}\{[(EP^iPr_2)(TeP^iPr_2)N]\} (E = S, Se, Te) have been prepared in order to determine the structures of the dichalcogenidoimidodiphosphinate anions when they are not coordinated to a cation. Finally, DFT calculations were carried out in order to elucidate the reasons for the observed experimental results in the aforementioned investigations (a) and (b).
Experimental Section

General Procedures. All reactions and manipulations of products were performed under an argon atmosphere by using standard Schlenk techniques or an inert atmosphere glovebox. The reagents (TMEDA)Li[(EPiPr2)(TeP2Pr2)N] (E = S, Se)\(^{31}\) and [(TeP2Pr2)2N]\(^{23}\) were prepared by literature methods. The solvents \(n\)-hexane and THF were dried by distillation over Na/benzophenone and stored over molecular sieves under an argon atmosphere prior to use. Iodine and cobaltocene were obtained from Aldrich and used as received.

Spectroscopic Methods. The \(^1\)H, \(^{13}\)C, \(^{31}\)P, \(^{77}\)Se and \(^{125}\)Te NMR spectra were obtained in \(d_8\)-THF on a Bruker DRX 400 spectrometer operating at 399.592, 100.489, 161.765, 76.223 and 126.082 MHz respectively. \(^1\)H and \(^{13}\)C spectra are referenced to the solvent signal. \(^{31}\)P, \(^{77}\)Se and \(^{125}\)Te spectra are referenced externally to an 85% solution of H\(_3\)PO\(_4\) in D\(_2\)O, a solution of (PhSe)\(_2\) in CDCl\(_3\) and to a solution of (PhTe)\(_2\) in CDCl\(_3\) respectively. Elemental analyses were performed by Analytical Services, Department of Chemistry, University of Calgary.

Synthesis of [(SPiPr2)(TeP2Pr2)N]I (2a). A solution of I\(_2\) (0.040 g, 0.158 mmol) in 15 mL of THF was cooled to -78\(^\circ\)C and added via cannula to a -78\(^\circ\)C solution of (TMEDA)Li[(SPiPr2)(TeP2Pr2)N] (0.085 g, 0.160 mmol) in 25 mL of THF. This was allowed to stir for 1 h at -78\(^\circ\)C and was then warmed to room temperature with stirring. Solvent was evaporated under vacuum and 50mL of \(n\)-hexane was added. This solution was warmed and then filtered through a microfilter (0.45 \(\mu\)m PTFE). The solution was reduced in volume to approx. 5mL and left overnight at -35\(^\circ\)C to yield orange crystals of
[(SPiPr2)(TePiPr2)N]I (2a) (0.086 g, 82 %). Elemental analysis calcd (%) for C12H28P2NSTeI: C 26.95, H 5.28, N 2.62; found: C 27.06, H 5.25, N 2.67. 1H NMR (d8-THF, 23°C): δ 2.74 [2 x sept, 3J(1H,1H) = 7 Hz, 2H, CH(CH3)2], 2.28 [2 x sept, 3J(1H,1H) = 7 Hz, 2H, CH(CH3)2], 1.42 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 18 Hz, 6H, CH(CH3)2], 1.37 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 21 Hz, 6H, CH(CH3)2], 1.26 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 18 Hz, 6H, CH(CH3)2]; 13C {1H} NMR: δ 30.31 [d, 1J(13C,31P) = 48 Hz, 1C, CH(CH3)2], 30.27 [d, 1J(13C,31P) = 48 Hz, 1C, CH(CH3)2], 28.86 [d, 1J(13C,31P) = 65 Hz, 1C, CH(CH3)2], 28.83 [d, 1J(13C,31P) = 65 Hz, 1C, CH(CH3)2], 17.45 [d, 2J(13C,31P) = 2 Hz, 2C, CH(CH3)2], 14.87 [d, 2J(13C,31P) = 3 Hz, 2C, CH(CH3)2], 14.65 [d, 2J(13C,31P) = 3 Hz, 2C, CH(CH3)2], 14.63 [d, 2J(13C,31P) = 2 Hz, 2C, CH(CH3)2]; 31P {1H} NMR: δ 89.9 [d, 2J(31P,31P) = 28 Hz, 2J(125Te,31P) = 36 Hz], 59.2 [d, 1J(125Te,31P) = 968 Hz, 2J(31P,31P) = 28 Hz]; 125Te NMR: δ 574 [dd, 1J(125Te,31P) = 968 Hz, 2J(125Te,31P) = 36 Hz].

Synthesis of [(SePiPr2)(TePiPr2)N]I (2b). The salt 2b was obtained as orange crystals (0.066 g, 71 %) from the reaction of (TMEDA)Li[(SePiPr2)(TePiPr2)N] (0.092 g, 0.159 mmol) with I2 (0.040 g, 0.158 mmol) by using a procedure identical to that described above for 2a. Elemental analysis calcd (%) for C12H28P2NSeTeI: C 24.77, H 4.85, N 2.41; found: C 25.05, H 5.09, N 2.75. 1H NMR (d8-THF, 23°C): δ 2.79 [2 x sept, 3J(1H,1H) = 7 Hz, 2H, CH(CH3)2], 2.34 [2 x sept, 3J(1H,1H) = 7 Hz, 2H, CH(CH3)2], 1.42 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 18 Hz, 6H, CH(CH3)2], 1.36 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 20 Hz, 6H, CH(CH3)2], 1.28 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 19 Hz, 6H, CH(CH3)2], 1.27 [dd, 3J(1H,1H) = 7 Hz, 3J(1H,31P) = 18 Hz, 6H, CH(CH3)2]; 13C {1H} NMR: δ 32.38 [d, 1J(13C,31P) = 48 Hz, 1C, CH(CH3)2], 32.34 [d, 1J(13C,31P) = 48 Hz, 1C, CH(CH3)2], 31.14
[d, $^1J(^{13}C, ^{31}P) = 58$ Hz, 1C, CH(CH$_3$)$_2$], \(31.10\) [d, $^1J(^{13}C, ^{31}P) = 58$ Hz, 1C, CH(CH$_3$)$_2$], \(19.29\) [d, $^2J(^{13}C, ^{31}P) = 2$ Hz, 2C, CH(CH$_3$)$_2$], \(17.01\) [d, $^2J(^{13}C, ^{31}P) = 2$ Hz, 2C, CH(CH$_3$)$_2$], \(16.88\) [d, $^2J(^{13}C, ^{31}P) = 4$ Hz, 2C, CH(CH$_3$)$_2$], \(16.69\) [d, $^2J(^{13}C, ^{31}P) = 3$ Hz, 2C, CH(CH$_3$)$_2$]; $^{31}P$ {\textsuperscript{1}H} NMR: $\delta$ 87.1 [d, $^1J(^{77}Se, ^{31}P) = 494$ Hz, $^2J(^{31}P, ^{31}P) = 30$ Hz, $^2J(^{125}Te, ^{31}P) = 30$ Hz], 62.5 [d, $^1J(^{125}Te, ^{31}P) = 967$ Hz, $^2J(^{31}P, ^{31}P) = 30$ Hz]; $^{77}Se$ NMR: $\delta$ -2 [dd, $^1J(^{77}Se, ^{31}P) = 494$ Hz, $^2J(^{77}Se, ^{31}P) = 9$ Hz]. $^{125}Te$ NMR: $\delta$ 504 [dd, $^1J(^{125}Te, ^{31}P) = 967$ Hz, $^2J(^{125}Te, ^{31}P) = 29$ Hz].

**Synthesis of (SP$^i$Pr$_2$NP$^i$Pr$_2$Te-)$_2$ (3a).** A solution of CoCp$_2$ (0.018 g, 0.095 mmol) in 15 mL of THF was added via cannula to a solution of [(SP$^i$Pr$_2$)(TeP$^i$Pr$_2$)]I (2a, 0.050 g, 0.093 mmol) in 25 mL of THF at room temperature and this was allowed to stir for 1 h. The resulting brown solution was filtered through a microfilter (0.45 µm PTFE) to remove the obvious fine precipitate and the solvent was evaporated under vacuum. The remaining dark solid was redissolved in n-hexane and left overnight at -35°C to yield dark crystals of (SP$^i$Pr$_2$NP$^i$Pr$_2$Te-)$_2$ (3a) (0.027 g, 71%). Elemental analysis calcd (%) for C$_{24}$H$_{56}$PaN$_2$S$_2$Te$_2$: C 35.33, H 6.91, N 3.43; found: C 35.24, H 7.07, N 3.29. \(^{1}H\) NMR (d$_{6}$-THF, 23°C): $\delta$ 2.42 [2 x sept, $^3J(^{1}H, ^{1}H) = 7$ Hz, 4H, CH(CH$_3$)$_2$], 1.98 [2 x sept, $^3J(^{1}H, ^{1}H) = 7$ Hz, 4H, CH(CH$_3$)$_2$], 1.39 [dd, $^3J(^{1}H, ^{1}H) = 7$ Hz, $^3J(^{1}H, ^{31}P) = 18$ Hz, 12H, CH(CH$_3$)$_2$], 1.30 [dd, $^3J(^{1}H, ^{1}H) = 7$ Hz, $^3J(^{1}H, ^{31}P) = 20$ Hz, 12H, CH(CH$_3$)$_2$], 1.15 [dd, $^3J(^{1}H, ^{1}H) = 7$ Hz, $^3J(^{1}H, ^{31}P) = 17$ Hz, 12H, CH(CH$_3$)$_2$], 1.14 [dd, $^3J(^{1}H, ^{1}H) = 7$ Hz, $^3J(^{1}H, ^{31}P) = 18$ Hz, 12H, CH(CH$_3$)$_2$]; \(^{13}C\) {\textsuperscript{1}H} NMR: $\delta$ 33.71 [d, $^1J(^{13}C, ^{31}P) = 52$ Hz, 2C, CH(CH$_3$)$_2$], 33.69 [d, $^1J(^{13}C, ^{31}P) = 52$ Hz, 2C, CH(CH$_3$)$_2$], 32.54 [d, $^1J(^{13}C, ^{31}P) = 70$ Hz, 2C, CH(CH$_3$)$_2$], 32.51 [d, $^1J(^{13}C, ^{31}P) = 70$ Hz, 2C, CH(CH$_3$)$_2$], 20.08 [s, 4C, CH(CH$_3$)$_2$], 17.80 [d, $^2J(^{13}C, ^{31}P) = 4$ Hz, 4C, CH(CH$_3$)$_2$], 17.51 [s, 4C, CH(CH$_3$)$_2$], 17.35 [d, $^2J(^{13}C, ^{31}P) = 3$ Hz, 1C, CH(CH$_3$)$_2$].
4C, CH(CH₃)₂]: ³¹P {¹H} NMR: δ 78.2 [d, ²J(³¹P,³¹P) = 26 Hz], 40.8 [d, ¹J(¹²⁵Te,³¹P) = 1011 Hz, ²J(³¹P,³¹P) = 26 Hz]; ¹²⁵Te NMR: δ 60 [d, ¹J(¹²⁵Te,³¹P) = 1002 Hz].

Synthesis of (SePPr₃NPPr₂Te)-₂ (3b). The compound 3b was obtained as dark crystals (0.021 g, 54%) from the reaction of [(SePPr₂)(TePPr₂)N]I (2b, 0.050 g, 0.086 mmol) with CoCp₂ (0.016 g, 0.085 mmol) by using a procedure identical to that described above for 3a. Elemental analysis calcd (%) for C₃₁H₆₆P₄N₂Se₂Te₂: C 31.69, H 6.20, N 3.08; found: C 31.36, H 6.40, N 3.05. ¹H NMR (d₆-THF, 23°C): δ 2.41 [2 x sept, ³J(¹H,¹H) = 7 Hz, 4H, CH(CH₃)₂], 2.05 [2 x sept, ³J(¹H,¹H) = 8 Hz, 4H, CH(CH₃)₂], 1.40 [dd, ³J(¹H,¹H) = 7 Hz, ³J(¹H,³¹P) = 18 Hz, 12H, CH(CH₃)₂], 1.30 [dd, ³J(¹H,¹H) = 7 Hz, ³J(¹H,³¹P) = 20 Hz, 12H, CH(CH₃)₂], 1.16 [dd, ³J(¹H,¹H) = 7 Hz, ³J(¹H,³¹P) = 17 Hz, 12H, CH(CH₃)₂], 1.15 [dd, ³J(¹H,¹H) = 7 Hz, ³J(¹H,³¹P) = 18 Hz, 12H, CH(CH₃)₂]; ¹³C {¹H} NMR: δ 33.89 [d, ¹J(¹³C,³¹P) = 52 Hz, 2C, CH(CH₃)₂], 33.86 [d, ¹J(¹³C,³¹P) = 52 Hz, 2C, CH(CH₃)₂], 33.07 [d, ¹J(¹³C,³¹P) = 62 Hz, 2C, CH(CH₃)₂], 33.04 [d, ¹J(¹³C,³¹P) = 62 Hz, 2C, CH(CH₃)₂], 20.07 [s, 4C, CH(CH₃)₂], 17.99 [s, 4C, CH(CH₃)₂], 17.92 [d, ²J(¹³C,³¹P) = 5 Hz, 4C, CH(CH₃)₂], 17.48 [d, ²J(¹³C,³¹P) = 3 Hz, 4C, CH(CH₃)₂]; ³¹P {¹H} NMR: δ 71.8 [d, ¹J(⁷⁷Se,³¹P) = 639 Hz, ²J(³¹P,³¹P) = 26 Hz], 41.7 [d, ¹J(¹²⁵Te,³¹P) = 1012 Hz, ²J(³¹P,³¹P) = 26 Hz]; ⁷⁷Se NMR: δ -177 [d, ¹J(⁷⁷Se,³¹P) = 658 Hz].¹²⁵Te NMR: δ 72 [d, ¹J(¹²⁵Te,³¹P) = 1009 Hz].

Synthesis of Cp₂Co[(SPPr₂)(TePPr₂)N] (4a). A solution of CoCp₂ (0.036 g, 0.190 mmol) in 15 mL of THF was added via cannula to a solution of [(SPPr₂)(TePPr₂)N]I (2a, 0.050 g, 0.093 mmol) in 25 mL of THF at room temperature and this was allowed to stir for 1 h. The resulting brown solution was filtered through a microfilter (0.45 µm PTFE) to remove the obvious fine precipitate and then the solution was reduced in
volume to approx. 3 mL. 7mL of n-hexane was added and this was left overnight at -35°C to yield dark crystals of Cp₂Co[(SP²Pr₂)(TeP²Pr₂)N] (4a) (0.042 g, 76 %). Elemental analysis calcd (%) for C₂₂H₃₈P₂NSTeCo: C 44.25, H 6.41, N 2.35; found: C 44.06, H 6.21, N 2.36. ¹H NMR (d₈-THF, 23°C): δ 5.83 [br s, 10H, Co(C₅H₅)₂] 2.01 [2 x sept, ³J(¹H,¹H) = 7 Hz, 2H, CH(CH₃)₂], 1.82 [2 x sept, ³J(¹H,¹H) = 7 Hz, 2H, CH(CH₃)₂], 1.22-1.11 [m, 24H, CH(CH₃)₂]; ¹³C {¹H} NMR: δ 35.56 [d, ¹J(¹³C,³¹P) = 54 Hz, 1C, CH(CH₃)₂], 35.52 [d, ¹J(¹³C,³¹P) = 54 Hz, 1C, CH(CH₃)₂], 33.31 [d, ¹J(¹³C,³¹P) = 75 Hz, 1C, CH(CH₃)₂], 19.62 [s, 2C, CH(CH₃)₂], 18.38 [s, 2C, CH(CH₃)₂], 18.30 [d, ²J(¹³C,³¹P) = 3 Hz, 2C, CH(CH₃)₂], 18.16 [d, ²J(¹³C,³¹P) = 3 Hz, 2C, CH(CH₃)₂]; ³¹P {¹H} NMR: δ 64.3 [d, ²J(³¹P,³¹P) = 25 Hz], 19.7 [d, ¹J(¹²⁵Te,³¹P) = 1540 Hz, ²J(³¹P,³¹P) = 25 Hz]; ¹²⁵Te NMR: δ -670 [d, ¹J(¹²⁵Te,³¹P) = 1536 Hz].

Synthesis of Cp₂Co[(SeP²Pr₂)(TeP²Pr₂)N] (4b). The salt 4b was obtained as dark crystals (0.038 g, 69 %) from the reaction of [(SeP²Pr₂)(TeP²Pr₂)N]I (2b, 0.050 g, 0.086 mmol) with CoCp₂ (0.032 g, 0.170 mmol) by using a procedure identical to that described above for 4a. Elemental analysis calcd (%) for C₂₂H₃₈P₂NSTeCo: C 41.03, H 5.95, N 2.18; found: C 40.91, H 6.03, N 2.30. ¹H NMR (d₈-THF, 23°C): δ 5.56 [br s, 10H, Co(C₅H₅)₂] 2.04 [2 x sept, ³J(¹H,¹H) = 7 Hz, 2H, CH(CH₃)₂], 1.87 [2 x sept, ³J(¹H,¹H) = 7 Hz, 2H, CH(CH₃)₂], 1.24-1.12 [m, 24H, CH(CH₃)₂]; ¹³C {¹H} NMR: δ 35.49 [d, ¹J(¹³C,³¹P) = 55 Hz, 1C, CH(CH₃)₂], 35.46 [d, ¹J(¹³C,³¹P) = 55 Hz, 1C, CH(CH₃)₂], 34.09 [d, ¹J(¹³C,³¹P) = 66 Hz, 1C, CH(CH₃)₂], 34.07 [d, ¹J(¹³C,³¹P) = 66 Hz, 1C, CH(CH₃)₂], 19.60 [s, 2C, CH(CH₃)₂], 18.73 [s, 2C, CH(CH₃)₂], 18.47 [d, ²J(¹³C,³¹P) = 3 Hz, 2C, CH(CH₃)₂], 18.27 [d, ²J(¹³C,³¹P) = 2 Hz, 2C, CH(CH₃)₂]; ³¹P {¹H} NMR: δ 57.8 [d,
\( ^1J(^{77}\text{Se},^{31}\text{P}) = 656 \text{ Hz}, \) \( ^2J(^{31}\text{P},^{31}\text{P}) = 25 \text{ Hz}, \) \( ^1J(^{125}\text{Te},^{31}\text{P}) = 1553 \text{ Hz}, \) \( ^2J(^{31}\text{P},^{31}\text{P}) = 25 \text{ Hz}, \) \( ^{77}\text{Se} \) NMR: \( \delta -276 \) \( [d, \ ^1J(^{77}\text{Se},^{31}\text{P}) = 664 \text{ Hz}]; \) \( ^{125}\text{Te} \) NMR: \( \delta -672 \) \( [d, \ ^1J(^{125}\text{Te},^{31}\text{P}) = 1599 \text{ Hz}]. \)

**Synthesis of \( \text{Cp}_2\text{Co[(TeP}^\text{iPr}_2]_2\text{N}} \) (4c).** The salt 4c was obtained as a dark red powder (0.060 g, 85 %) from the reaction of \([(\text{TeP}^\text{iPr}_2]_2\text{N}]\text{I} \) (2c, 0.064 g, 0.102 mmol) with \( \text{CoCp}_2 \) (0.039 g, 0.206 mmol) by using a procedure identical to that described above for 4a. Elemental analysis calcd (%) for \( \text{C}_{22}\text{H}_{38}\text{P}_2\text{N}\text{Te}_2\text{Co} \): C 38.15, H 5.53, N 2.02; found: C 38.49, H 5.86, N 1.85. \( ^1\text{H} \) NMR (d\(_8\)-THF, 23°C): \( \delta 1.94 \) [sept, \( ^3J(^1\text{H},^1\text{H}) = 7 \text{ Hz}, 4\text{H}, \) CH(CH\(_3\))\(_2\)], 1.22-1.14 [m, 24H; CH(CH\(_3\))\(_2\)]; \( ^{13}\text{C} \) \( ^1\text{H} \) NMR: \( \delta 35.28 \) [d, \( ^1J(^{13}\text{C},^{31}\text{P}) = 65 \text{ Hz}, 2\text{C}, \) CH(CH\(_3\))\(_2\)], 35.22 [d, \( ^1J(^{13}\text{C},^{31}\text{P}) = 65 \text{ Hz}, 2\text{C}, \) CH(CH\(_3\))\(_2\)], 19.13 [s, 4C, CH(CH\(_3\))\(_2\)], 17.87 [s, 4C, CH(CH\(_3\))\(_2\)]; \( ^{31}\text{P} \) \( ^1\text{H} \) NMR: \( \delta 23.5 \) [s, \( ^1J(^{125}\text{Te},^{31}\text{P}) = 1571 \text{ Hz}; \) \( ^{125}\text{Te} \) NMR: \( \delta -680 \) [d, \( ^1J(^{125}\text{Te},^{31}\text{P}) = 1575 \text{ Hz}]. \)

**X-ray crystallography.** Crystals of 2a, 2b, 3a, 3b, 4a, 4b and 4c were coated with Paratone 8277 oil and mounted on a glass fiber. Diffraction data were collected on a Nonius KappaCCD diffractometer using Mo K\( \alpha \) radiation (\( \lambda = 0.71073 \text{ Å} \)) at -100°C. The unit-cell parameters were calculated and refined from the full data set. Crystal cell refinement and data reduction were carried out using the Nonius DENZO package. After data reduction, the data were corrected for absorption based on equivalent reflections using SCALEPACK (Nonius, 1998). The structure of 3b was solved by Patterson techniques; all other structures were solved by direct methods using SHELXS-97 \(^{32} \) while refinements were carried out on \( F^2 \) against all independent reflections by the full-matrix least-squares method by using the SHELXL-97 program. \(^{33} \) The hydrogen atoms were
calculated geometrically and were riding on their respective atoms, and all non-hydrogen atoms were refined with anisotropic thermal parameters.

Crystallographic data are summarized in Table 1. The structures of 2a, 2b, 3a, 3b, 4a and 4c were well-ordered and no special considerations were necessary. The structure of 4b displayed positional disorder of the tellurium and selenium sites which was modeled as an anisotropic 50:50 mixture.

**Computational Details.** DFT calculations were performed for various geometrical and conformational isomers of compounds 3 (see text for details). The molecular structures were optimized by using a combination of the PBE exchange-correlation functional \(^{34-36}\) with the Ahlrichs' triple-zeta valence basis set augmented by one set of polarization functions (def-TZVP);\(^{37}\) for tellurium the corresponding ECP basis set was used.\(^{38}\) All calculations were performed with the Turbomole 5.10 program package.\(^{39}\) Visualizations for Figure 3 were done with the gOpenMol program.\(^{40,41}\)

**Results and Discussion**

**Synthesis and Crystal Structures of 2a and 2b.** The reaction of the heterodichalcogenidoimidoimidodiphosphinates 1a and 1b with one equivalent of iodine in THF at -78° C proceeded smoothly to give the salts 2a and 2b in good yields according to Scheme 1.
The identity of these new cations was confirmed by multinuclear NMR spectra. The $^{31}$P NMR spectrum of 2a consists of a pair of mutually coupled doublets at 89.9 and 59.2 ppm which are, as expected, considerably deshielded with respect to the corresponding anion 1a (66.1, 21.6 ppm). The peak representing the tellurium-bound phosphorus atom (P-Te) displays characteristic $^{125}$Te satellites, with $^1J$(Te-P) = 968 Hz, cf. 1040 Hz for the ditellurido cation in 2c. The P-S resonance also displays satellites with a separation of 36 Hz, tentatively attributed to a $^2J$(Te-P) coupling as a consequence of the presence of a S-Te bond. A downfield shift is also observed in the $^{125}$Te NMR spectrum of 2a, for which a doublet of doublets is centered at +574 ppm (cf. -757 ppm in
1a). The $^1J$(Te-P) and $^2J$(Te-P) coupling constants of 968 and 36 Hz, respectively, are consistent with those observed in the $^{31}$P NMR spectrum.

The NMR spectra of 2b are analogous to those of 2a. The $^{31}$P NMR spectrum displays a pair of doublets at 87.1 and 62.5 ppm with selenium (494 Hz) and tellurium (967 Hz) satellites, respectively. The chemical shifts are deshielded and the coupling constants are noticeably smaller than those of the corresponding anion 1b (59.0 ppm, $^1J$(Se-P) = 600 Hz; 23.6 ppm, $^1J$(Te-P) = 1426 Hz). While the signal at 87.1 ppm also clearly displays a second set of $^{125}$Te satellites with $^2J$(Te-P) = 30 Hz, the analogous $^{77}$Se satellites on either side of the signal at 62.5 ppm are not well-resolved. However, the $^{77}$Se NMR spectrum consists of a doublet of doublets centered at -2 ppm with $^1J$(Se-P) and $^2J$(Se-P) coupling constants of 494 and 9 Hz, respectively. This $^{77}$Se chemical shift is considerably downfield with respect to that of 1b (-319 ppm).

X-ray crystallographic analyses confirmed that the structures of 2a (Figure 1) and 2b (Figure 2) consist of a cationic five-membered ring and an iodide anion. Selected bond parameters are given in Table 2, along with the corresponding parameters of the ditellurido cation 2c for comparison. In both cases, the rings are distinctly puckered (E-P-P-Te dihedral angles are 24.74(3)$^\circ$ and 29.04(2)$^\circ$, respectively), in accordance with the conformation of 2c, but in contrast to the related planar 6 $\pi$-electron cations [(TeENSN)Cl]$^+$ (E = S, Se).42-45

The iodide anion in 2a displays a much stronger interaction with tellurium (2.915(1) Å) than with sulfur (3.991(1) Å). Indeed, this latter distance is close to the sum of the van der Waals radii of S and Te (4.00 Å) and can therefore be considered non-bonding. The Te-I interaction is also evident in the structure of 2b, where the Te-I
distance is 3.005(1) Å. In this derivative there is clearly no Se-I interaction, the closest selenium-iodine distance being greater than 6 Å. In both cases, the Te-I interaction is stronger than the corresponding interaction in the ditellurido cation 2c (3.430(1) Å).

Previous DFT calculations on the homodichalcogenido salts [(EPPr$_2$)$_2$N]I (E = Se, Te) showed that donation of electron density from the lone pair of the iodide anion into the LUMO ($\sigma^*$ E-E) of the cationic ring results in elongation of the E-E bond.$^{23}$ Simple qualitative MO theory arguments predict that in the mixed chalcogen systems the LUMO should be polarized towards the more electropositive chalcogen, i.e. tellurium, leading to preferential interaction of the iodide anion with the Te center of the cation. This is borne out by DFT calculations as illustrated in Figure 3. Since the I-Te contacts in 2a and 2b are shorter than those in 2c, stronger electron donation into the antibonding $\sigma^*$ (E-Te) orbital (E = S, Se) is expected, resulting in a reduced E-Te bond order and more pronounced elongation of the chalcogen-chalcogen bonds as observed in the crystal structures. The S-Te bond in 2a (2.710(1) Å) displays an elongation of ca. 12 % with respect to typical S-Te bond lengths (2.41-2.43 Å) in compounds where both chalcogens are two-coordinate.$^{43,45}$ Likewise, the Se-Te bond is elongated in 2b by ca. 8 % when compared with Se-Te bonds in similar molecules, e.g. [(TeSeNSN)Cl]$^+$ cation (2.53-2.54 Å).$^{42,45}$ The calculated Pauling bond orders$^{47}$ of these E-Te bonds are 0.38 and 0.51 for 2a and 2b, respectively [cf. 2c; 4 % elongation, bond order 0.72]. The trends in the observed lengthening of chalcogen-chalcogen bonds in these cyclic cations are summarized in Table 3.

The stronger Te-I interactions of 2a and 2b result in lengthening of the Te-P distance by more than 0.1 Å with respect to that of 2c [2.500(1) Å (2a); 2.497(1) Å (2b);
2.396(3) Å (2c)]. The Se-P bond of 2b (2.205(1) Å) is only slightly shorter than the corresponding bond in the diselenido cation [(SePPr$_2$)$_2$N]I (2.229(2) Å),$^{23}$ possibly because there is no Se-I interaction in 2b. The P-N bond lengths are similar in both complexes and their average values are close to those of 2c.

The P-N-P bond angles of 2a (128.5(2)$^\circ$) and 2b (128.4(2)$^\circ$) are ca. 5$^\circ$ narrower than that of 2c (133.5(4)$^\circ$). The Te-P-N bond angles are all similar in 2a and 2b falling within the range 109.0(1)-109.6(2)$^\circ$. Concomitantly with the lengthening of the E-Te and E-P bonds going from 2a to 2c, the E-Te-P bond angle becomes progressively larger [82.89(2)$^\circ$ (2a); 84.68(3)$^\circ$ (2b); 88.56(5)$^\circ$ (2c)]. This trend is compensated by successively smaller Te-E-P bond angles [97.95(3)$^\circ$ (2a); 92.60(3)$^\circ$ (2b); 88.36(5)$^\circ$ (2c)].

**Synthesis and Crystal Structures of 3a and 3b.** The ditelluride dimer 3c was obtained by the one-electron oxidation of the corresponding anion 1c with half-an-equivalent of iodine.$^{22}$ However, the analogous stoichiometric reaction of 1a or 1b with I$_2$ failed to yield the respective dimers 3a and 3b. The $^{31}$P NMR spectra of these reactions displayed a plethora of peaks, with the principal resonances attributable to the products of a two-electron oxidation (i.e. 2a and 2b). Consequently, an alternative synthetic route to 3a and 3b was devised, namely the one-electron reduction of the cations 2a and 2b (Scheme 1). Cobaltocene was chosen for this reduction since it is of moderate reducing strength.$^{48}$

The synthetic method employed could potentially give rise to three different dimers through association of the initially formed radicals [EPPr$_2$NPPPr$_2$Te]$^\bullet$, namely a Te-Te, an E-E or a Te-E (E = S, Se) bound dimer. The $^{31}$P NMR spectra of the products obtained from cobaltocene reductions of 2a and 2b exhibited a pair of mutually coupled
doublets with appropriate Te (and Se in 3b) satellites, suggesting the formation of only one of these three possible isomers. The $^1J$(Te-P) coupling constants of 3a (1011 Hz) and 3b (1012 Hz.) are of similar magnitude to that of the bridging-Te bound phosphorus signal in 3c (1026 Hz), indicating that the product is a Te-Te bridged dimer (the $^1J$(Te-P) coupling constant of the terminal Te-bound phosphorus signal in 3c is 1500 Hz). Furthermore, the $^1J$(Se-P) coupling constant of 639 Hz in 3b is comparable to the value of 642 Hz reported for the terminal P=Se groups in the dimer (SeP$_2$NP$_2$Se-)$_2$.27

The $^{125}$Te (and $^{77}$Se) NMR spectra of 3a and 3b each display appropriate $^1J$(E-P) coupling constants. The $^{77}$Se chemical shift of -177 ppm for 3b is comparable with the value of -145 ppm for the terminal selenium atom in (SeP$_2$NP$_2$Se-)$_2$ (cf. +242 ppm for bridging Se).27 The poor solubility of 3c makes it impossible to compare the $^{125}$Te chemical shifts of 3a (60 ppm) and 3b (79 ppm). The $^{77}$Se and $^{125}$Te chemical shifts in 3a and 3b all occur at intermediate values with respect to the corresponding anions 1a,b and cations 2a,b.

X-ray crystallographic analyses of 3a (Figure 4) and 3b (Figure 5) confirm that the NMR-based assignment of a Te-Te bound dimer is correct in both cases. Pertinent bond parameters are compared with those of (TeP$_2$NP$_2$Te-)$_2$ (3c) in Table 2. Like 3c, the heterodichalcogenido (Se/Te) system 3b is centrosymmetric and hence displays a P-Te-Te-P dihedral angle of 180°. By contrast the S/Te derivative 3a, which is not centrosymmetric, shows a much smaller corresponding dihedral angle (131.06(5)°). The most interesting feature of these structures is the Te-Te bond length. As indicated in Table 3, the Te-Te bond (2.807(1) Å) in 3a is elongated by ca. 3 % with respect to a Te-Te bond of an organic ditelluride or the [Te-Te]$^2$ dianion, while the Te-Te bond in 3b
(2.893(1) Å) is elongated by ca. 6% (cf. 2.946(1) Å in 3c; 8% elongation).\textsuperscript{22} The smaller elongation of the central Te-Te bond in the heterodichalcogenido dimers 3a and 3b can be attributed to the polarization of the SOMO of the neutral radicals towards the Te centers, cf. the LUMOs of the cyclic cations 2a and 2b (Figure 3). The polarization leads to better overlap of the orbitals involved in the Te-Te bond formation and, consequently, to a stronger Te-Te bond. This conclusion is further supported by DFT calculations, which show that the dimers 3a and 3b are bound by 131 and 107 kJ mol\textsuperscript{-1} in comparison to two acyclic neutral radicals [EP\textsuperscript{i}Pr\textsubscript{2}NP\textsuperscript{i}Pr\textsubscript{2}Te]\textsuperscript{•}, (E = S and Se, respectively), cf. 80 kJ mol\textsuperscript{-1} for E = Te.

A possible minor contribution to the elongation of the Te-Te bond in the centrosymmetric dimers 3b and 3c may be attributed to the P-Te-Te-P dihedral angles (both 180\textdegree). Calculations have previously shown that Te-Te bonds are moderately elongated (in HTeTeH)\textsuperscript{50} when this dihedral angle is either 0 or 180\textdegree, since the repulsions of the lone pairs on adjacent tellurium atoms will be maximized in such a conformation.

The Te-P and P-N bond lengths are similar in 3a and 3b and in accordance with those reported for 3c. Like 3c, the P(2)-N bond lengths of 3a and 3b are slightly longer than the P(1)-N bond lengths. The P-S bond of 3a (1.981(2) Å) is intermediate between the P-S distances of neutral (SP\textsuperscript{i}Pr\textsubscript{2})\textsubscript{2}NH (ave. 1.945(1) Å)\textsuperscript{51} and the cation 2a (2.033(1) Å). Likewise, the P-Se bond length in 3b (2.152(1) Å) falls between the corresponding distances in (SeP\textsuperscript{i}Pr\textsubscript{2})\textsubscript{2}NH (ave. 2.099(1) Å)\textsuperscript{52} and 2b (2.205(1) Å). The bond angles in the EPNPTe backbone of 3a and 3b are similar, with a minor increase in P-N-P and Te-P-N angles and a slight decrease in the E-P-N angle along the series 3a-3c.
The four chalcogen atoms of 3a and 3b lie in an almost linear arrangement, which is achieved by a distinct twisting of the five-membered EPNPTe backbone as evidenced by the Te-P(1)-P(2)-E dihedral angles [29.13(8)° (3a), 28.60(3)° (3b)]. This deformation is similar in magnitude to those reported for 3c (29.53(6)°) and the cationic rings 2a-2c.

**Synthesis and Crystal Structures of 4a, 4b and 4c.** The successful one-electron reduction of the cationic species 2a and 2b with cobaltocene paves the way for an investigation of the two-electron reduction with two equivalents of cobaltocene to regenerate the corresponding anions (Scheme 1). Such anions are expected to exist as part of an ion-separated salt with a cobaltocenium cation. The reactions of 2a and 2b with cobaltocene in a 1:2 molar ratio produce 4a and 4b as crystalline materials in good yields; the cobaltocenium salt of the ditellurido anion 4c is also obtained from the analogous reaction of [(TePPr2)_2N]I (2c) with two equivalents of cobaltocene. The presence of the cobaltocenium cation is confirmed by the 1H NMR spectra of 4a and 4b, which each reveal a broad singlet at 5.83 and 5.56 ppm, respectively. The corresponding signal in 4c is too broad to be observed. The resonance for the [CoCp2]^+ cation in the 13C NMR spectra of all three products is not evident, presumably because it is too broad. 31P NMR analysis of these three products shows similar chemical shifts to those of the contact ion pairs 1a-1c. The ion-separated complexes 4a and 4b display a pair of mutually coupled doublets while 4c shows the expected singlet. In each case, the chemical shifts are within 2 ppm of those of 1a-1c. The tellurium satellites in 4a-4c all exhibit a 1J(Te-P) coupling constant (1540–1571 Hz) similar to that of the ion-separated salt [Me2Al(TMEDA)][(TePPr2)2N] (1560 Hz) and intermediate in value between those of
the chelated anions (1a-1c, 1416-1470 Hz) and the monotelluride Te=P^iPr_2-N=P(H)^iPr_2 (1654 Hz),\textsuperscript{22} which contains a terminal P=Te double bond. These coupling constants reflect the lack of coordination to the anion and suggest that the bond order in solution is intermediate between that of a single and double bond. A similar intermediate $^1J(\text{Se-P})$ coupling constant is found for 4b (664 Hz; cf. 599 Hz in 1b and 684 Hz in Se=P^iPr_2-N=P(H)^iPr_2).\textsuperscript{31} The $^{125}\text{Te}$ (and $^{77}\text{Se}$) NMR spectra each display the expected doublets with appropriate chalcogen-phosphorus coupling, although the signals are noticeably deshielded with respect to those of the contact ion pairs 1a-1c.

The X-ray crystal structures of compounds 4a-4c confirm that they exist as ion-separated salts (Figures 6-8). Table 2 contains selected bond parameters. The P-N bond lengths are in a narrow range and are consistent with those of the lithium-bound salts 1a-1c. The Te-P bonds are ca. 0.1 Å shorter than those of 1a-1c, in accordance with the conclusion of a higher bond order drawn from the $^1J(\text{Te-P})$ coupling constants (vide supra). The S-P bond of 4a (2.005(1) Å) is slightly longer than those seen in the limited number of non-coordinated salts containing the [(SP^iPr_2)_2N]^- anion (1.971(2) – 1.987(2) Å).\textsuperscript{54-58} A similar lengthening is also observed for the Se-P bond of 4b (2.169(7) Å) when compared with the same bond in the non-coordinated anions [(SeP^iPr_2)_2N]^- (2.128(1) Å)\textsuperscript{59} and [(SeP^iPr_2)(OP^iPr_2)N]^- (2.140(2) Å).\textsuperscript{60}

The P-N-P bond angles in 4b (135.8(2)°) and 4c (136.2(3)°) are similar and considerably narrower than that of 4a (146.9(2)°). Indeed, 4a displays a P-N-P bond angle that is 2° larger than that in 1a, while this angle in 4b and 4c is more than 7° narrower than those of the chelated salts 1b and 1c. The widening of the P-N-P bond angle in 4a has an influence on the twisting of the EPNPTe backbone as reflected in the
S-P-P-Te dihedral angle of 36.45(5)°, which is ca. 2° smaller than that of 1a (38.92(5)°). The narrower P-N-P bond angles in 4b and 4c lead to much greater distortion from planarity; the E-P-P-Te dihedral angles are greater than 75°. This increased twisting is substantially greater than that observed in 1b (41.1(5)°) and 1c (43.33(6)°), in which the chalcogen atoms are pulled towards one another by the lithium cation. These E-P-P-Te dihedral angles in 4b and 4c are similar to those reported for the neutral complexes (EP'Pr₂)₂NH (E = S, Se), whose corresponding dihedral angles are 79° \(^{51}\) and 80°\(^{52}\) respectively.

**Theoretical Investigations of Structural and Conformational isomers of 3.** Three different conformational isomers have been observed experimentally for the dichalcogenide dimers 3 in the solid state:\(^{22,27,53}\) one \(C_2\)-symmetric conformation (E = Se, R = \(^{1}\)Pr) and two \(C_1\) symmetric conformations (E = Te, R = \(^{1}\)Pr or E = Se, R = \(^{3}\)Bu; and E = S, R = \(^{3}\)Bu) that differ by the orientation of the terminal chalcogen atoms. In addition, an interesting structural dichotomy has been established for the all-tellurium species:\(^{27,53}\) a Te-Te bonded dichalcogenide dimer (3c) is observed when the substituents at phosphorus are \(^{1}\)Pr groups, whereas a contact ion pair structure (5) is obtained for the analogous \(^{1}\)Bu-substituted species. We have recently analyzed the energy hypersurfaces of the homodichalcogenide dimers 3 computationally and the results showed that (a) the three conformational isomers are generally very close in energy and (b) the stability of the contact ion pair structure 5 increases relative to that of the dichalcogenide structure 3 as one descends the series of chalcogens from sulfur to tellurium.\(^{27}\)
The polarization of the SOMOs of the neutral radicals [ER₂PNR₂PTe]⁺ (E = S, Se) towards Te readily explains the preferential dimerization through Te-Te bond formation \textit{(vide supra)}. We have also probed the energetics of the dimerization process by performing geometry optimizations for both 3a and 3b as well as for their unknown E-Te and E-E (E = S, Se) bonded structural isomers 3d-3g. The possibility for conformational isomerism was also taken into account in the calculations and optimizations for all dimers were started from three different conformers analogous to those observed for the known dichalcogenides 3 in the solid state (C₂ and two C₁ isomers, \textit{vide supra}).

The calculations correctly identify the experimentally observed Te-Te bonded isomers 3a and 3b as the lowest energy structures on the potential energy hypersurface. Of the three possibilities available, the E-E bonded dimers 3f and 3g are the highest in energy in both series: the energy difference with respect to the corresponding dimers with a Te-Te linkage is found to be 100 and 48 kJ mol⁻¹ for sulfur and selenium, respectively. The asymmetrically bonded S-Te and Se-Te alternatives are also energetically disfavored though by a much smaller margin. The calculated energy differences are 42 and 22 kJ mol⁻¹ for 3d and 3e, respectively. For all isomers studied, the C₁ symmetric (or “C₁-like” for 3d and 3e) conformer with the two terminal chalcogen atoms significantly twisted away from planarity is always the highest in energy by approximately 50 kJ mol⁻¹. For 3a, b, f and g the C₁ symmetric conformer with a linear chalcogen “chain” as well as the
structure with a $C_2$ axis have virtually the same energy since the calculated difference is less than the accuracy of the applied DFT method (only a few kJ mol$^{-1}$). In contrast, only the “$C_2$–like” conformer could be found for the asymmetrically bonded 3d and 3e.

Previous experimental work established the existence of the intriguing contact ion pair structure 5 for the ditelluride dimer when the substituents on the phosphorus atoms are changed from $^3$Pr to the more bulky $^4$Bu groups.$^{27}$ DFT calculations of this structural dichotomy showed that the contact ion pair structure 5 is indeed more energetically favorable (by -20 kJ mol$^{-1}$) than the ditelluride structure 3 ($E = \text{Te}$, $R = ^4\text{Bu}$), whereas there is no clear structural preference for the corresponding all-selenium systems and the disulfide structure is more stable for the all-sulfur derivative.$^{27}$ This raises the interesting question of whether a contact ion pair structure is energetically preferred for the mixed chalcogen systems 3a and 3b when the substituents on the phosphorus atoms are $^4$Bu rather than $^3$Pr. Interestingly, DFT calculations predict that the contact ion pair structure is 10 kJ mol$^{-1}$ lower in energy than the Te-Te bonded dimer for the mixed chalcogen (Se/Te) system whereas, for the S/Te system, the Te-Te bonded dimer is lower in energy by a very small margin (ca. 3 kJ mol$^{-1}$).
**Figure 1.** Thermal ellipsoid plot of 2a (50 % probability). All hydrogen atoms have been omitted for clarity.

**Figure 2.** Thermal ellipsoid plot of 2b (50 % probability). All hydrogen atoms have been omitted for clarity.
**Figure 3.** Frontier orbitals in the cyclic cations [(EPiPr2)(TePiPr2)]+ (E = S, Se). In each case, the Te atom is on the right hand side of the E-Te linkage.

**Figure 4.** Thermal ellipsoid plot of 3a (50 % probability). All hydrogen atoms have been omitted for clarity.
Figure 5. Thermal ellipsoid plot of 3b (50 % probability). All hydrogen atoms have been omitted for clarity.

Figure 6. Thermal ellipsoid plot of the anion of 4a (50 % probability). All hydrogen atoms have been omitted for clarity.
Figure 7. Thermal ellipsoid plot of one of the 50% occupancy models of the anion of 4b (50 % probability). All hydrogen atoms have been omitted for clarity.

Figure 8. Thermal ellipsoid plot of the anion of 4c (50 % probability). All hydrogen atoms have been omitted for clarity.
Table 1. Crystallographic data for [(SP\textsuperscript{3}Pr\textsubscript{2})(TeP\textsubscript{3}Pr\textsubscript{2})N]|I (2a), [(SeP\textsuperscript{3}Pr\textsubscript{2})(TeP\textsubscript{3}Pr\textsubscript{2})N]|I (2b), (SP\textsuperscript{3}Pr\textsubscript{2}NP\textsuperscript{3}Pr\textsubscript{2}Te-)\textsubscript{2} (3a), (SeP\textsuperscript{3}Pr\textsubscript{2}NP\textsuperscript{3}Pr\textsubscript{2}Te-)\textsubscript{2} (3b), Cp\textsubscript{2}Co[(SP\textsuperscript{3}Pr\textsubscript{2})(TeP\textsubscript{3}Pr\textsubscript{2})N] (4a), Cp\textsubscript{2}Co[(SeP\textsuperscript{3}Pr\textsubscript{2})(TeP\textsubscript{3}Pr\textsubscript{2})N] (4b) and Cp\textsubscript{2}Co[(TeP\textsubscript{3}Pr\textsubscript{2})\textsubscript{2}N] (4c)

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\textsuperscript{a} λ (Mo Kα) = 0.71073 Å. \textsuperscript{b} R1 = \frac{\sum|F_o|-|F_c|}{\sum|F_o|}. \textsuperscript{c} wR2 = \sqrt{\frac{\sum w(F_o^2 - F_c^2)^2}{\sum wF_o^4}}^{1/2}
Table 2. Selected Bond Lengths (Å) and Bond Angles (°) for complexes 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b and 4c [Calculated Pauling Bond Orders in Square Brackets]45

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<tr>
<th></th>
<th>2a</th>
<th>2b</th>
<th>2c</th>
<th>3a</th>
<th>3b</th>
<th>3c</th>
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<td>E(1)-P(2)-N(1)</td>
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<td>146.9(2)</td>
<td>135.8(2)</td>
<td>136.2(3)</td>
</tr>
</tbody>
</table>

Symmetry operation: a 2 - x, 1 - y, 2 - z. cation: – x, -x + y, ½ - z. anion: 2/3 + x - y, 1/3 - y, 5/6 - z. d 2/3 + x - y, 1/3 - y, 5/6 - z. 

d The bond parameters for the other half of dimer 3a are within experimental error of the first half shown above and are not given.

e Te(1A) = Te(2). f P(2) = P(1A). g P(1A) = P(3). h E(1) = Te(1A).
Table 3. Elongation of Te-E bonds in cyclic cations (2) and dimers (3).

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<th>% elongation</th>
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<td>2.807(1) (Te-Te)</td>
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<tr>
<td>3c (^{22})</td>
<td>2.946(1) (Te-Te)</td>
<td>8</td>
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**Conclusions**

The interaction of the iodide anion and the tellurium atom of the cyclic heterodichalcogenido cations \([(E^{i}P^{i}Pr_{2})(Te^{i}P^{i}Pr_{2})N]^{+} (E = S, Se)\) is stronger than that found in the ditellurido salt \([(Te^{i}P^{i}Pr_{2})_{2}N]I\). A major consequence of this interaction is the lengthening of the E-Te bond by up to 12%. On the basis of DFT calculations, the pronounced elongation of the E-Te bonds is attributed to the polarization of the LUMO (\(\sigma^{*} E-Te\)) towards tellurium in the cations. Dimers of the type \((E^{i}P^{i}Pr_{2}NP^{i}Pr_{2}Te-)_{2} (E = S, Se)\) are obtained by the novel route of reducing the corresponding cations with cobaltocene. A combination of multinuclear NMR and X-ray crystallographic studies revealed that these dimers exist solely as the Te-Te bonded isomer in solution and in the solid state. The central Te-Te bond length decreases along the series E = Te, Se, S as a result of the polarization of the SOMO of the neutral radicals \([E^{i}P^{i}Pr_{2}NP^{i}Pr_{2}Te]^{-}\) towards Te when E = S or Se, resulting in stronger Te-Te overlap. DFT calculations of relative energies confirm that the formation of Te-Te bonded dimers is significantly more favorable than the structural isomers involving E-Te or E-E bonds. Interestingly, however, a change of the substituents on phosphorus from \(^{i}Pr\) to \(^{i}Bu\) is predicted to tip the
energy balance in favor of a contact ion pair structure for the Te-Te bonded dimer when E = Se. Two-electron reduction of the cations \([\text{E}^\text{PPr}_2\text{(TePPr}_2\text{)}\text{N}]^+ (\text{E} = \text{S, Se, Te})\) with cobaltocene regenerates the corresponding anions as ion-separated cobaltocenium salts. The structural analysis of these salts represents the first systematic study of a series of ion-separated dichalcogenidoimidodiphosphinate anions with a common cation.

**Acknowledgment.** The authors gratefully acknowledge the Natural Sciences and Engineering Research Council (Canada) (SDR and TC) and the Academy of Finland (HMT) for funding. We also thank Jamie Ritch and Dr. Jari Konu for assistance with the X-ray crystal structure determinations.

**Supporting Information Available:** X-ray crystallographic files in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org

**References**


47. The bond orders were calculated by the Pauling Equation \( N = 10^{(D-R)/0.71} \) where \( R \) is the observed bond length (Å). The single bond length \( D \) is estimated from the sums of appropriate covalent radii (Å): Te-S 2.41, Te-Se 2.54, Te-Te 2.74, Te-I 2.70.


