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Stereoselective hetero Diels-Alder reaction of selenoaldehydes with pentavalent phosphole chalcogenides

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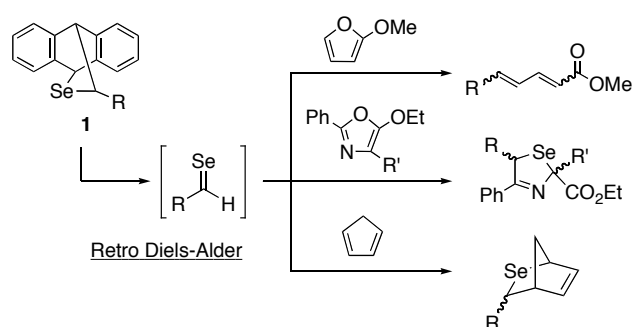
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Abstract—Stereoselective hetero Diels-Alder reaction of selenoaldehydes, generated by thermal retro Diels-Alder reaction of anthracene cycloadducts, with pentavalent 3,4-dimethylphosphole chalcogenides at 110°C in toluene to give the corresponding [4+2] cycloadducts as a single diastereoisomer in good yields, accompanied by a slight scrambling of chalcogen atoms. Higher reaction temperature led to an increase of the scrambling between chalcogen atoms.

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Hetero Diels-Alder reaction has been a potentially powerful synthetic tool and also a useful approach for the construction of heteroatom-containing cyclic ring system, which often results in high stereo- and regioselective observations.¹ Nitrogen, oxygen, or sulfur atom containing heterodienophiles such as imines, aldehydes, or thiocarbonyl compounds have been extensively developed in this hetero Diels-Alder methodology.² On the other hand, selenoaldehydes, being very reactive selenium analogues of aldehydes, have been considered to be highly reactive dienophiles in cycloaddition reactions³ and recently to play an increasingly important role in the preparation of selenium-containing heterocycles.⁴ In this context, we have already reported an efficient method for the synthesis of reactive selenocarbonyl compounds using $(\text{Me}_2\text{Al})_2\text{Se}$ as a selenating agent,⁵ and recently found that selenoaldehyde-anthracene cycloadducts **1** can serve as convenient and clean precursors of selenoaldehydes via thermal retro Diels-Alder reaction.⁶ The cycloadducts **1** were easily prepared from reaction of the corresponding aldehydes with $(\text{Me}_2\text{Al})_2\text{Se}$ in the presence of anthracene in good yields according to our previously reported procedure.^{5c}

Utilizing this retro Diels-Alder reaction of **1**, we have already reported the reactions of selenoaldehydes with 2-methoxyfuran⁷ and 5-ethoxyoxazoles⁸ as shown in Scheme 1. In the reaction with 2-methoxyfuran, penta-2,4-dienoates were obtained in good yields along with the deposition of

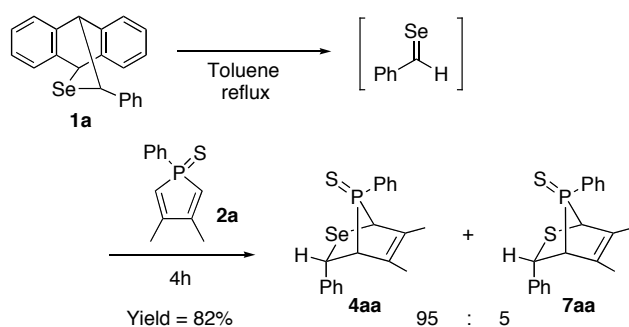


Scheme 1.

elemental selenium. On the other hand, the reaction with 5-ethoxyoxazoles gave the five-membered ring compounds having 3-selenazoline structure in good yields via the carbon-selenium bond cleavage in the [4+2] cycloadducts and the successive recyclization. Simple cyclopentadiene reacted with selenoaldehydes to give the [4+2] cycloadducts as a mixture of endo and exo isomers. Thus, the reactions of selenoaldehydes with five-membered ring cyclic dienes involving heteroatoms afforded interesting results, and these results prompted us to examine the reaction of selenoaldehydes with phosphorus-containing five-membered ring dienes, which would be also expected for the formation of new heterocyclic compounds involving selenium and phosphorus atoms. We selected pentavalent phosphole chalcogenides, 3,4-dimethylphosphole sulfides and selenides, as cyclic dienes having a phosphorus atom because of easy preparation and well-known reactivity of dienic system.⁹ In this paper we describe stereoselective [4+2] cycloaddition of selenoaldehydes, generated by thermal retro Diels-Alder reaction of **1**, with pentavalent 3,4-dimethylphosphole chalcogenides to give the

Keywords: Selenoaldehyde; Cycloaddition reaction; Phosphole sulfide; Phosphole selenide; Selenium-containing heterocycle.

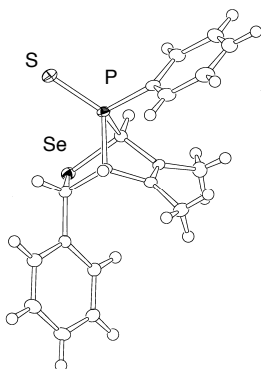
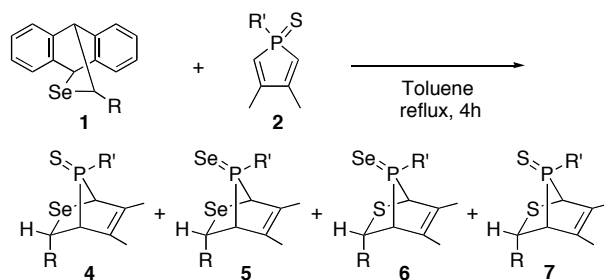
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Scheme 2.

corresponding [4+2] cycloadducts as a single diastereoisomer.

Pentavalent 1-phenyl or 1-benzylphosphole chalcogenides (**2a,b** and **3a,b**) were prepared by treatment of the corresponding trivalent 3,4-dimethylphosphole¹⁰ and elemental sulfur or selenium. The toluene solution of **1a** (R=Ph) and 3,4-dimethyl-1-phenylphosphole 1-sulfide (**2a**) was heated at reflux for 4h to give two kinds of [4+2] cycloadducts with a 95:5 ratio in 82% yield. We, at first, thought that obtained two cycloadducts were a relationship of diastereoisomers, but very interestingly, after the detail analysis of the spectral data, it turned out that the minor product was the [4+2] cycloadduct with the corresponding thioaldehyde as shown in Scheme 2. This result suggests the reaction of selenoaldehyde with phosphole sulfide leads to the formation of the corresponding thioaldehyde in situ. On the other hand, the structure of major product (**4aa**) was supported by the analysis of NMR spectra and mass spectrum with a molecular ion peak at m/z 390.¹¹ Although the formation of four diastereoisomers is possible with respect to both asymmetric carbon originated from the selenoaldehyde and phosphorus centers in this cycloaddition, only one diastereoisomer was obtained with a complete stereoselectivity. The relative stereochemistry of this major product was finally confirmed by X-ray crystallography as depicted in Figure 1.¹² This shows clearly that two chalcogen atoms of sulfur and selenium are located in the same site and the pheny substituent

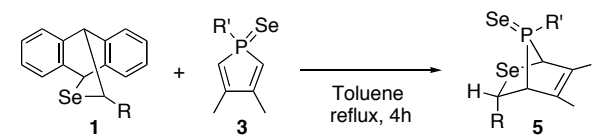
Figure 1. Crystal structure of cycloadduct **4aa**.Table 1. Hetero Diels-Alder reaction of aromatic selenoaldehydes with 3,4-dimethylphosphole sulfides **2**

1 R=	2 R' =	Yield (%) ^a	Product ratio ^b 4 : 5 : 6 : 7
Ph (a)	Ph (a)	82	95 : - : - : 5
<i>p</i> -NCC ₆ H ₄ (b)	Ph (a)	97	99 : - : - : 1
<i>p</i> -MeOC ₆ H ₄ (c)	Ph (a)	92	95 : - : - : 5
Ph (a)	Bn (b)	78	97 : - : - : 3
<i>p</i> -NCC ₆ H ₄ (b)	Bn (b)	87	90 : 4 : 1 : 5
<i>p</i> -MeOC ₆ H ₄ (c)	Bn (b)	91	91 : 4 : 1 : 4

^a Isolated yield. ^b Determined by ¹H NMR.

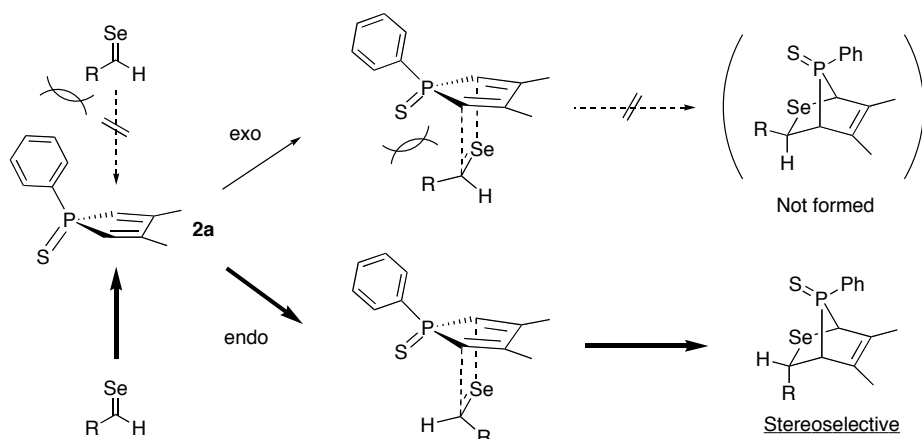
originated from selenoaldehyde is situated in the endo position.

Several anthracene cycloadducts **1** (R=Ar) with an aromatic substituent were heated with phosphole sulfide **2a** (R'=Ph) or **2b** (R'=Bn) in toluene at reflux for 4h to give mainly the corresponding [4+2] cycloadducts (**4**) of selenoaldehydes with phosphole sulfide in good yields as a single diastereoisomer. In all cases, minor products **5-7**, in which the combination of two chalcogen atoms in the cycloadducts is different, were obtained in small amounts as mentioned above. The results are shown in Table 1. The stereochemistry of major products was predicted to be same as that of adduct **4aa** by comparing with chemical shifts and coupling constants in NMR spectra.¹³ Next, we have examined the reaction of aromatic selenoaldehydes with phosphole selenides **3a** (R'=Ph) or **3b** (R'=Bn) under similar reaction conditions. In this reaction, a scrambling of

Table 2. Hetero Diels-Alder reaction of aromatic selenoaldehydes with 3,4-dimethylphosphole selenides **3**

1 R=	3 R' =	Cycloadduct	Yield (%) ^a
Ph (a)	Ph (a)	5aa	65
<i>p</i> -NCC ₆ H ₄ (b)	Ph (a)	5ba	79
<i>p</i> -MeOC ₆ H ₄ (c)	Ph (a)	5ca	69
Ph (a)	Bn (b)	5ab	71
<i>p</i> -NCC ₆ H ₄ (b)	Bn (b)	5bb	89
<i>p</i> -MeOC ₆ H ₄ (c)	Bn (b)	5cb	97

^a Isolated yield.



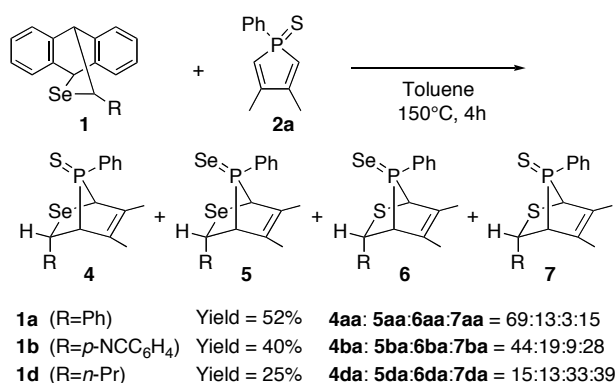
Scheme 3.

chalcogen atoms is of course impossible because of the same selenium atom in both reactants. As an expected result, a single diastereoisomer **5**, being identical with one of minor products in Table 1, in each entry was obtained in good yield with the above-mentioned complete stereoselectivity. The results are shown in Table 2.¹⁴ Furthermore, to confirm the structure of other minor products **6** and **7** in Table 1, we independently conducted the reaction of the corresponding thioaldehydes¹⁵ with phosphole sulfides **2** or selenides **3** in toluene under similar reaction conditions. All signals in ¹H and ¹³C NMR spectra of the obtained cycloadducts were completely consistent with those of two minor products in Table 1.

The observed complete stereoselectivity can be accounted for by the following considerations as shown in Scheme 3, though the speculations. In the approach of selenoaldehyde to two faces of five-membered phosphole ring, a large steric repulsion between the R' (R²=Ph or Bn) substituent on phosphorus atom and the selenoaldehyde appears to be a significant factor. Accordingly, selenoaldehyde prefers the access to the site of sulfur atom selectively. On the other hand, regarding the face selectivity of selenoaldehyde, there exists a large steric repulsion between sulfur atom on phosphorus and the R group in an exo addition. As a result,

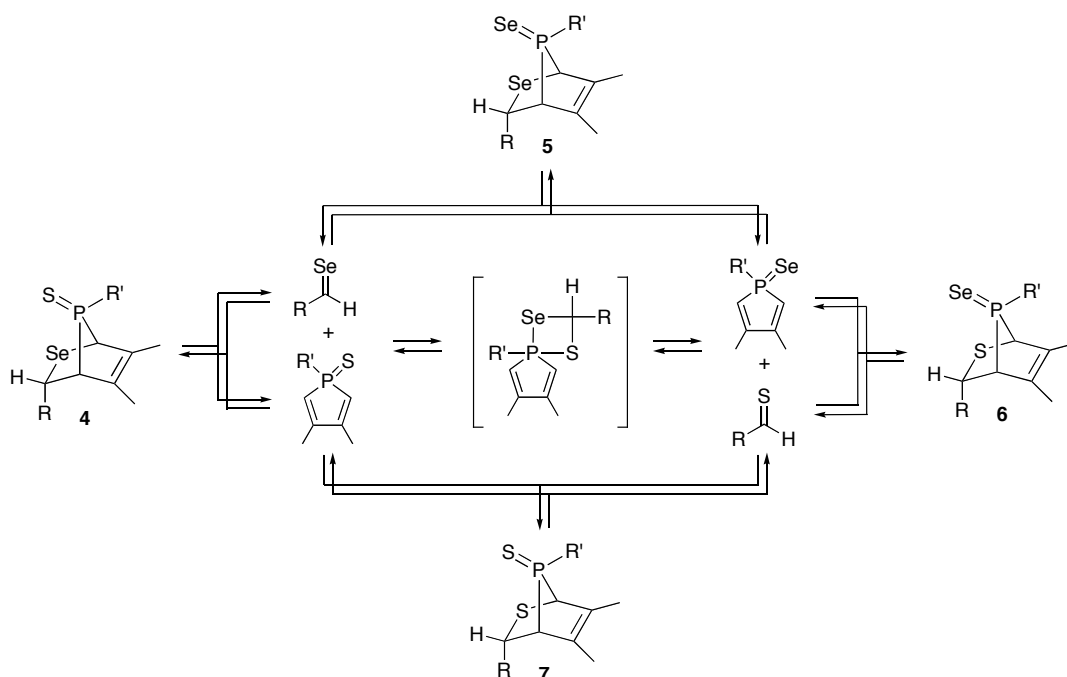
the endo addition of selenoaldehyde proceeds selectively to afford only one diastereoisomer among possible four diastereomers.

Next we tried the reaction of aliphatic selenoaldehydes with phosphole sulfide. Retro Diels-Alder reaction of **1** with an aliphatic substituent did not take place at a reflux temperature in toluene due to the stability, but the heating at over 150°C resulted in an efficient regeneration of aliphatic selenoaldehydes in situ. Thus, **1d** (R=*n*-Pr) was heated with phosphole sulfide **2a** at 150°C in toluene to give a mixture of four cycloadducts **4da**, **5da**, **6da**, and **7da** with a 15:13:33:39 relative ratio in low total yield. This result indicates higher reaction temperature may cause an increase of scrambling of sulfur and selenium atoms. To make sure the temperature effect, we examined the reaction of aromatic selenoaldehydes with **2a** at 150°C for 4h in toluene, and as a result four cycloadducts **4-7** were obtained in moderate yields. The results at 150°C summarized in Scheme 4. In addition, the heating of one cycloadduct **4ba** at 150°C for 4h in toluene resulted in the formation of a mixture of four cycloadducts **4ba-7ba** with a 42:24:5:29 ratio. This result indicates a thermal retro Diels-Alder reaction of cycloadducts **4** proceeded easily at 150°C and the exchange of chalcogen atoms occurred somewhere under these conditions.



Scheme 4.

Based on the above results, the most likely pathway for the scrambling of sulfur and selenium atoms in the cycloadducts may be as follows. It seems that selenoaldehydes undergo a [4+2] hetero Diels-Alder reaction with phosphole sulfide, whereas can also cause an exchange of chalcogen atoms at over 110°C via a probable four-membered ring intermediate¹⁶ to give the corresponding thioaldehydes and phosphole selenide. Thus, four compounds, selenoaldehyde, thioaldehyde, phosphole sulfide, and phosphole selenide, coexist in the reaction mixture and four combinations are possible for hetero Diels-Alder reaction to afford cycloadducts **4-7**. Furthermore, these cycloadducts undergo reversibly a retro Diels-Alder reaction at over 110°C. A plausible mechanism for exchange of chalcogen atoms is shown in Scheme 5.



Scheme 5. Plausible mechanism for exchange of chalcogen atoms.

In conclusion, we have demonstrated that the reaction of selenoaldehydes with pentavalent 3,4-dimethylphosphole chalcogenides at 110°C proceeded efficiently to give new bicyclic [4+2] cycloadducts involving both selenium and phosphorus atoms as a single diastereoisomer with complete stereoselectivity in good yields. At higher reaction temperature (> 110°C), a significant exchange of chalcogen atoms between selenoaldehyde and phosphole sulfide occurred, resulting in the formation of a mixture of four cycloadducts **4-7**. This result suggests these phosphole chalcogenides can serve as a new chalcogenating reagent for carbonyl compounds. We are currently investigating about the possibility and will report the results of our findings in due course.

Acknowledgments

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 - Cycloadduct **4aa**: mp 184-186°C, ¹H NMR (270 MHz, CDCl₃): δ 1.21 (s, 3H), 1.86 (s, 3H), 3.19 (br s, 1H), 4.05 (br d, *J* = 3.5 Hz, 1H), 5.80 (br s, 1H), 7.22-7.62 (m, 10H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.45 (d, *J* = 5.1 Hz), 16.44 (d, *J* = 5.6 Hz), 48.74 (d, *J* = 46.8 Hz), 53.37 (d, *J* = 13.4 Hz), 60.77 (d, *J* = 53.6 Hz), 127.28, 128.15, 128.35 (d, *J* = 11.2 Hz), 129.19, 129.76 (d, *J* = 8.9 Hz), 130.58, 130.67, 132.01 (d, *J* = 77.2 Hz), 137.75 (d, *J* = 12.8 Hz), 138.85 (d, *J* = 11.1 Hz); Mass (EI mode): *m/z* (relative intensity) 115 (13.2), 143 (16.8), 149 (19.5), 188 (19.8), 205 (45.9), 220 (100), 249 (33.0), 277 (19.7), 309 (24.2), 388 (25.5), 390 (M⁺, 50.8); HRMS calcd for C₁₉H₁₉PSSe (M⁺) 390.0110, found 390.0103.
 - Crystal data for **4aa**: C₁₉H₁₉PSSe, colourless crystalline solid, 0.35×0.25×0.10 mm³; formula weight = 389.35. Triclinic, space group: *P* $\bar{1}$. Unit cell dimensions: *a* = 10.8449(9), *b* = 11.1393(8), *c* = 16.9388(9), α = 90.860(7), β = 97.655(6), γ = 119.077(6) at 123K, *V* = 1764.9(2), *Z* = 4, *R* = 0.031 and *R*_w = 0.052 for 7466 reflections (*I* > 3.00σ(*I*)), GOF = 1.29.
 - Selected spectral data of cycloadducts **4**. Compound **4ba**: mp 186-187°C, ¹H NMR (270 MHz, CDCl₃): δ 1.20 (s, 3H), 1.88 (s, 3H), 3.19 (br s, 1H), 4.11 (br d, *J* = 3.2 Hz, 1H), 5.79 (br s, 1H), 7.39-7.61 (m, 9H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.58 (d, *J* = 5.0 Hz), 16.46 (d, *J* = 5.0 Hz), 49.23 (d, *J* = 46.8 Hz), 53.06 (d, *J* = 14.5 Hz), 59.77 (d, *J* = 53.6 Hz), 111.17, 118.32, 128.50 (d, *J* = 11.7 Hz), 129.83 (d, *J* = 11.2 Hz), 130.13, 130.91, 130.95, 131.94, 132.05, 138.55 (d, *J* = 12.3 Hz), 145.06 (d, *J* = 11.1 Hz); Mass (EI mode): *m/z* (relative intensity) 188 (48.7), 205 (25.0), 220 (100), 302 (93.0), 335 (21.4), 413 (18.5), 415 (M⁺, 37.5); HRMS calcd for C₂₀H₁₈NPSSe (M⁺) 415.0063, found 415.0061. Compound **4ab**: ¹H NMR (270 MHz, CDCl₃): δ 1.38 (s, 3H), 1.98 (s, 3H), 2.76 (br s, 1H), 3.44-3.62 (m, 3H), 5.63 (br s, 1H), 7.23-7.31 (m, 10H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.38 (d, *J* = 5.6 Hz), 16.58 (d, *J* = 6.2 Hz), 34.79 (d, *J* = 43.5 Hz), 48.61 (d, *J* = 42.9 Hz), 53.81 (d, *J* = 11.7 Hz), 59.39 (d, *J* = 49.1 Hz), 127.03 (d, *J* = 3.4 Hz), 127.25, 128.11, 128.36 (d, *J* = 2.8 Hz), 129.08, 129.18, 130.13 (d, *J* = 6.1 Hz), 132.78 (d, *J* = 8.4 Hz), 137.42 (d, *J* = 12.8 Hz), 138.87 (d, *J* = 10.6 Hz); Mass (EI mode): *m/z* (relative intensity) 91 (43.4), 143 (100), 201 (27.2), 234 (19.5), 249 (17.6), 402 (23.8), 404 (M⁺, 47.4); HRMS calcd for C₂₀H₂₁PSSe (M⁺) 404.0267, found 404.0259. Compound **4cb**: ¹H NMR (270 MHz, CDCl₃): δ 1.42 (s, 3H), 1.98 (s, 3H), 2.72 (br s, 1H), 3.38-3.59 (m, 3H), 3.77 (s, 3H), 5.60 (br s, 1H), 6.76 (d, *J* = 8.6 Hz, 2H), 7.15 (d, *J* = 8.6 Hz, 2H), 7.26-7.31 (m, 5H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.47 (d, *J* = 5.6 Hz), 16.75 (d, *J* = 6.2 Hz), 34.97 (d, *J* = 43.5 Hz), 48.68 (d, *J* = 42.9 Hz), 53.35 (d, *J* = 11.7 Hz), 55.27, 59.52 (d, *J* = 49.1 Hz), 113.61, 127.15 (d, *J* = 3.3 Hz), 128.49 (d, *J* = 2.8 Hz), 129.25 (d, *J* = 5.0 Hz), 130.31, 130.85 (d, *J* = 10.6 Hz), 132.94 (d, *J* = 8.3 Hz), 137.56 (d, *J* = 12.3 Hz), 158.77; Mass (EI mode): *m/z* (relative intensity) 91 (70.9), 143 (100), 200 (30.3), 231 (42.2), 234 (22.2), 279 (31.8), 432 (23.9), 434 (M⁺, 46.9); HRMS calcd for C₂₁H₂₃OPSSe (M⁺) 434.0372, found 434.0374.
 - Selected spectral data of cycloadducts **5**. Compound **5aa**: mp 174-176°C, ¹H NMR (270 MHz, CDCl₃): δ 1.19 (s, 3H), 1.85 (s, 3H), 3.27 (br s, 1H), 4.13 (br d, *J* = 4.0 Hz, 1H), 5.86 (br s, 1H), 7.24-7.59 (m, 10H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.60 (d, *J* = 5.0 Hz), 16.48 (d, *J* = 5.0 Hz), 49.06 (d, *J* = 38.5 Hz), 53.37 (d, *J* = 15.1 Hz), 59.98 (d, *J* = 46.3 Hz), 127.39, 128.24, 128.39 (d, *J* = 11.7 Hz), 129.28, 129.66 (d, *J* = 8.9 Hz), 130.69 (d, *J* = 2.2 Hz), 131.05 (d, *J* = 4.5 Hz), 132.90 (d, *J* = 67.5 Hz), 138.04 (d, *J* = 11.7 Hz), 138.69 (d, *J* = 11.7 Hz); Mass (EI mode): *m/z* (relative intensity) 178 (41.4), 188 (25.9), 205 (22.2), 266 (48.7), 268 (100), 277 (52.1), 436 (30.9), 438 (M⁺, 34.4); HRMS calcd for C₁₉H₁₉PSe₂ (M⁺) 437.9555, found 437.9554. Compound **5ba**: mp 171-172°C, ¹H NMR (270 MHz, CDCl₃): δ 1.19 (s, 3H), 1.87 (s, 3H), 3.26 (br s, 1H), 4.17 (br d, *J* = 4.0 Hz, 1H), 5.85 (br s, 1H), 7.38-7.59 (m, 9H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.74 (d, *J* = 4.5 Hz), 16.54 (d, *J* = 5.0 Hz), 49.57 (d, *J* = 38.0 Hz), 53.12 (d, *J* = 16.2 Hz), 60.04 (d, *J* = 46.8 Hz), 111.38, 118.39, 128.57 (d, *J* = 11.7 Hz), 129.76 (d, *J* = 8.9 Hz), 130.22, 130.57 (d, *J* = 4.5 Hz), 131.02 (d, *J* = 2.2 Hz), 132.08, 132.38 (d, *J* = 68.6 Hz), 138.88 (d, *J* = 11.7 Hz), 144.92 (d, *J* = 11.7 Hz); Mass (EI mode): *m/z* (relative intensity) 58 (47.7), 187 (35.6), 188 (32.9), 205 (29.9), 266 (49.3), 268 (100), 302 (48.9), 459 (11.5), 461 (20.1), 463 (M⁺, 22.4); HRMS calcd for C₂₀H₁₈NPSe₂ (M⁺) 462.9507, found 462.9491. Compound **5ab**: mp 172-174°C, ¹H NMR (270 MHz, CDCl₃): δ 1.36 (s, 3H), 1.96 (s, 3H), 2.83 (br s, 1H), 3.56-3.76 (m, 3H), 5.68 (br s, 1H), 7.22-7.30 (m, 10H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.43 (d, *J* = 5.6 Hz), 16.58 (d, *J* = 6.2 Hz), 36.54 (d, *J* = 35.1 Hz), 48.89 (d, *J* = 35.2 Hz), 54.10 (d, *J* = 12.8 Hz), 59.62 (d, *J* = 43.0 Hz), 127.19 (d, *J* = 3.3 Hz), 127.34, 128.18, 128.41 (d, *J* = 3.4 Hz), 129.16 (d, *J* = 5.0 Hz), 129.27, 130.43 (d, *J* = 4.5 Hz), 132.79 (d, *J* = 8.3 Hz), 137.62 (d, *J* = 11.1 Hz), 138.69 (d, *J* = 10.6 Hz); Mass (EI mode): *m/z* (relative intensity) 91 (100), 191 (41.6), 201 (38.3), 280 (22.3), 282 (45.7), 449 (17.5), 451 (M⁺, 18.9); HRMS calcd for C₂₀H₂₁PSe₂ (M⁺) 451.9711, found 451.9695. Compound **5cb**: ¹H NMR (270 MHz, CDCl₃): δ 1.41 (s, 3H), 1.96 (s, 3H), 2.79 (br s, 1H), 3.46-3.83 (m, 3H), 3.76 (s, 3H), 5.65 (br s, 1H), 6.76 (d, *J* = 8.9 Hz, 2H), 7.15 (d, *J* = 8.9 Hz, 2H), 7.30-7.58 (m, 5H); ¹³C NMR (67.5 MHz, CDCl₃): δ 13.41 (d, *J* = 5.0 Hz), 16.64 (d, *J* = 5.6 Hz), 36.56 (d, *J* = 35.1 Hz), 48.82 (d, *J* = 35.2 Hz), 53.49 (d, *J* = 13.9 Hz), 55.19, 59.56 (d, *J* = 41.8 Hz), 113.53, 127.16 (d, *J* = 3.3 Hz), 128.39 (d, *J* = 2.8 Hz), 129.15 (d, *J* = 5.0 Hz), 130.25, 130.44 (d, *J* = 18.9 Hz), 130.55, 132.80 (d, *J* = 8.3 Hz), 137.61 (d, *J* = 11.1 Hz), 158.68; Mass (EI mode): *m/z* (relative intensity) 91 (100), 191 (48.0), 200 (95.2), 202 (53.4), 231 (64.6), 280 (33.9), 282 (61.2), 321 (97.2), 480 (20.7), 482 (M⁺, 22.3); HRMS calcd for C₂₁H₂₃OPSe₂ (M⁺) 481.9817, found 481.9854.
 - Thioaldehydes were similarly generated in situ by retro Diels-Alder reaction of thioaldehyde-anthracene cycloadducts which were prepared by reaction of the corresponding aldehydes with (Me₂Al)₂S¹⁷ in the presence of anthracene at reflux in toluene.
 - Oxygen-selenium exchange reactions via a similar four-membered ring intermediate using pentavalent phosphorus compound with a P=Se group (PhP(Se)Cl₂) have been already reported; Michael, J. P.; Reid, D. H.; Rose, B. G.; Speirs, R. A. *J. Chem. Soc., Chem. Commun.* **1988**, 1494-1496.
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