

## Mechanism of Catalytic Addition of Benzeneselenol to Alkynes\*

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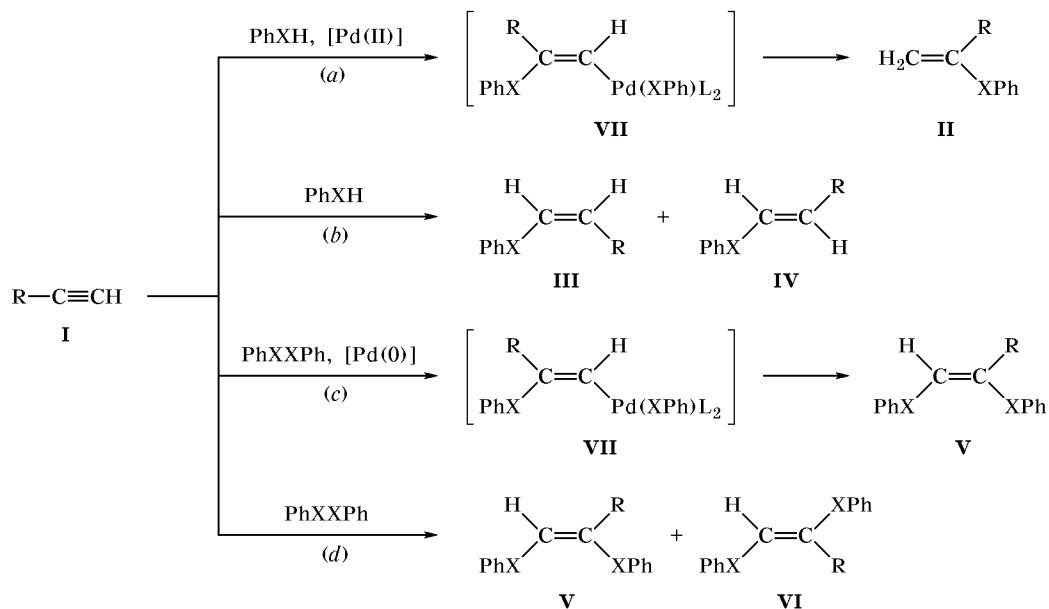
**Abstract**—Addition of benzeneselenol to terminal alkynes  $\text{HC}\equiv\text{CR}$ , catalyzed by Pd(0) complexes, leads to formation of mixtures of mono- and bis(phenylseleno)alkenes, depending on the nature of the R substituent. Electron-donor groups ( $\text{R} = \text{Bu}, \text{CH}_2\text{OH}, \text{CH}_2\text{NMe}_2$ ) give rise to addition according to the Markownikoff rule, whereas from alkynes with electron-acceptor groups ( $\text{R} = \text{Ph}, \text{COOMe}$ ) mixtures of products are formed as a result of side reactions. A probable reaction mechanism includes oxidative addition of benzeneselenol to the metal, alkyne insertion into the Pd–Se bond, and reductive elimination.

In the recent time, extensive development of the chemistry of organoselenium compounds is observed due to their growing application in both organic synthesis [1–4] and material science [5, 6]. The most promising ways for building up new selenium–carbon

bonds are based on addition reactions which are characterized by high chemoselectivity.

According to published data,  $\text{Pd}(\text{OAc})_2$  catalyzes addition of benzenethiol [7–10] and benzeneselenol [11] at the triple bond of alkynes **I**, following the

**Scheme 1.** Addition of  $\text{PhXH}$  and  $\text{Ph}_2\text{X}_2$  to alkynes ( $\text{X} = \text{S}, \text{Se}$ ).



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**Table 1.** Catalytic and noncatalytic addition of benzeneselenol to alkynes<sup>a</sup>

Alkyne	Catalytic reaction <sup>b</sup>		Noncatalytic reaction <sup>b</sup>	
	overall yield, %	ratio <b>II</b> : <b>III</b> : <b>IV</b> : <b>V</b>	overall yield, %	ratio <b>II</b> : <b>III</b> : <b>IV</b> : <b>V</b>
HC≡CC <sub>4</sub> H <sub>9</sub> ( <b>Ia</b> )	74	1.0:0.0:0.0:0.5	0	–
HC≡CCH <sub>2</sub> NMe <sub>2</sub> ( <b>Ib</b> )	83	1.0:0.0:0.0:1.0	0	–
HC≡CCH <sub>2</sub> OH ( <b>Ic</b> )	56	1.0:0.0:0.0:1.8	0	–
HC≡CPh ( <b>Id</b> )	~100	1.1:3.4:1.0:0.0	80	0.0:3.7:1.0:0.0
HC≡CCOOMe ( <b>Ie</b> )	~100	0.0:4.5:1.2:1.0 <sup>c</sup>	80	0.0:10.0:1.0:0.0

<sup>a</sup> The yields were determined by NMR spectroscopy.

<sup>b</sup> For reaction conditions, see Experimental.

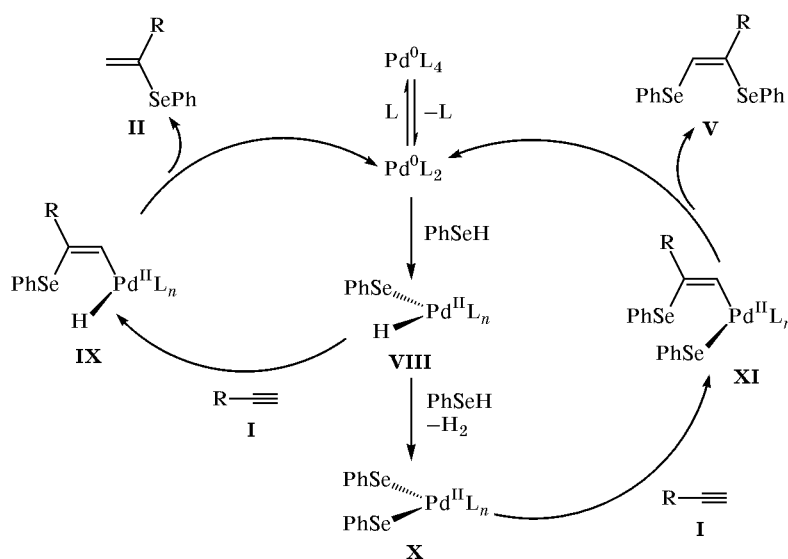
<sup>c</sup> A mixture of bis-adducts **Ve** and **VIe** at a ratio of 1.5:1.0.

Markownikoff pattern and yielding monosubstituted products **II** (Scheme 1, pathway *a*). In the noncatalytic reaction (which follows a radical mechanism), anti-Markownikoff adducts **III** and **IV** are formed [12, 13] (Scheme 1, pathway *b*). Palladium complexes catalyze addition of Ph<sub>2</sub>S<sub>2</sub> and Ph<sub>2</sub>Se<sub>2</sub> at the triple bond to give the corresponding bis(phenylthio)- and bis(phenylseleno)alkenes **V** [14, 15] (Scheme 1, pathway *c*), whereas the respective noncatalytic reaction results in formation of *E/Z*-isomeric disubstituted compounds **V** and **VI** [12, 16–18] (Scheme 1, pathway *d*). It is important that the key intermediate in both catalytic processes is bis-chalcogenide metal complex **VII**; however, no formation of disubstituted products **V** and **VI** was observed in the addition of PhXH [7–11, 14] (Scheme 1, pathway *a*). Unlike the radical process, the catalytic addition in both cases

(PhXH and Ph<sub>2</sub>X<sub>2</sub>) is characterized by high stereoselectivity.

With the goal of elucidating the mechanism of addition of benzeneselenol to acetylenic hydrocarbons we performed a detailed study using modern two-dimensional NMR techniques. We have found that in the presence of Pd(PPh<sub>3</sub>)<sub>4</sub> a mixture of compounds **II–V** is formed, whose composition depends on the R substituent (Table 1).

In the examined reactions we observed both mono- (**II**) and bis-addition (**V**) to the triple bond of alkynes (Table 1); moreover, anti-Markownikoff adducts **III** and **IV** were also formed from alkynes with electron-acceptor substituents (R = Ph, COOMe). By carrying out the reaction in the absence of Pd(PPh<sub>3</sub>)<sub>4</sub> we showed that compounds **III** and **IV** are formed as a result of noncatalytic process (Table 1). Probably,

**Scheme 2.**

**Table 2.**  $^1\text{H}$  and  $^{77}\text{Se}$  NMR parameters of the addition products of benzeneselenol to alkynes ( $\text{CDCl}_3$ ,  $\delta$ , ppm,  $J$ , Hz)

Comp. no.	$^1\text{H}$ NMR			$^{77}\text{Se}\{^1\text{H}\}$ NMR
	vinyl protons	substituent R	SePh	
<b>IIa</b>	5.50 br.s (1H), 5.12 s (1H)	2.30 br.t (2H, $\alpha\text{-CH}_2$ , $J = 7.4$ ), 1.53 t.t (2H, $\beta\text{-CH}_2$ , $J = 7.4, 7.5$ ) 1.32 t.q (2H, $\gamma\text{-CH}_2$ , $J = 7.4, 7.5$ ) 0.90 t (2H, $\delta\text{-CH}_2$ , $J = 7.4$ )	7.56–7.30 m (5H, $\text{H}_{\text{arom}}$ )	423.5
<b>IIb</b>	5.60 br.s (1H), 4.91 s (1H)	3.15 br.s (2H, $\text{CH}_2$ ), 2.28 s (6H, $\text{CH}_3$ )	7.62–7.32 m (5H, $\text{H}_{\text{arom}}$ )	419.1
<b>IIc</b>	5.89 br.s (1H), 5.44 s (1H)	4.19 br.s (2H, $\text{CH}_2$ )	7.55–7.30 m (5H, $\text{H}_{\text{arom}}$ )	385.6
<b>II d</b>	5.90 br.s (1H), 5.38 s (1H)	7.65–7.25 m (5H, $\text{H}_{\text{arom}}$ )	7.57–7.24 m (5H, $\text{H}_{\text{arom}}$ )	431.7
<b>III d</b>	6.97 d (1H, $J = 10.3$ ), 6.78 d (1H, $J = 10.3$ )	7.65–7.25 m (5H, $\text{H}_{\text{arom}}$ )	7.58–7.29 m (5H, $\text{H}_{\text{arom}}$ )	377.5
<b>III e</b>	7.76 d (1H, $J = 9.5$ ), 6.37 d (1H, $J = 9.5$ )	3.79 s (3H, $\text{CH}_3$ )	7.60–7.33 m (5H, $\text{H}_{\text{arom}}$ )	491.3
<b>IV d</b>	7.20 d (1H, $J = 15.8$ ), 6.87 d (1H, $J = 15.8$ )	7.65–7.25 m (5H, $\text{H}_{\text{arom}}$ )	7.59–7.38 m (5H, $\text{H}_{\text{arom}}$ )	389.8
<b>IV e</b>	8.15 d (1H, $J = 15.5$ ), 5.88 d (1H, $J = 15.5$ )	3.69 s (3H, $\text{CH}_3$ )	7.58–7.25 m (5H, $\text{H}_{\text{arom}}$ )	416.1
<b>V a</b>	6.93 br.s (1H)	2.28 br.t (2H, $\alpha\text{-CH}_2$ , $J = 7.4$ ), 1.50 t.t (2H, $\beta\text{-CH}_2$ , $J = 7.4, 7.5$ ) 1.23 t.q (2H, $\gamma\text{-CH}_2$ , $J = 7.4, 7.5$ ) 0.82 t (2H, $\delta\text{-CH}_2$ , $J = 7.4$ )	7.57–7.22 m (10H, $\text{H}_{\text{arom}}$ )	394.0, 386.6
<b>V b</b>	7.28 br.s (1H)	3.04 br.s (2H, $\text{CH}_2$ ), 2.22 s (6H, $\text{CH}_3$ )	7.28–7.59 m (10H, $\text{H}_{\text{arom}}$ )	403.0, 378.4
<b>V c</b>	7.41 br.s (1H)	4.17 br.s (2H, $\text{CH}_2$ ),	7.31–7.60 m (10H, $\text{H}_{\text{arom}}$ )	405.1, 341.5
<b>V e</b>	8.92 s (1H)	3.71 s (3H, $\text{CH}_3$ )	7.29–7.62 m (10H, $\text{H}_{\text{arom}}$ )	462.9, 356.7
<b>V l e</b>	7.92 s (1H)	3.83 s (3H, $\text{CH}_3$ )	7.32–7.49 m (10H, $\text{H}_{\text{arom}}$ )	535.5, 435.1

the latter is also responsible for the greater overall yield observed in the catalytic transformations of phenylacetylene and methyl 2-propynoate.

The structure of all products was established directly in the reaction mixtures using two-dimensional LR-COSY and heteronuclear inverse  $^1\text{H}$ – $^{77}\text{Se}$  (HMQC) techniques. The substitution pattern at the double bond was determined by the two-dimensional NOESY technique. The NMR parameters of the products are given in Table 2.

The reaction under study is characterized by simultaneous occurrence of two catalytic processes leading to formation of mono- and bis-phenylseleno-substituted compounds. A probable mechanism is shown in Scheme 2. It includes initial oxidative addition at the Se–H bond with formation of hydride complex **VIII**. The subsequent alkyne insertion into the Pd–Se bond and reductive elimination from inter-

mediate **IX** leads to compound **II**. It should be noted that no insertion into the Pd–H bond occurs in this system, otherwise the catalytic addition would follow the anti-Markownikoff pattern. In the presence of excess benzeneselenol, complex **VIII** can be converted into palladium diselenide **X** which in turn could give rise to bis(phenylseleno)alkene **V** via insertion and reductive elimination stages.

When the catalytic addition of benzeneselenol to 2-propynyl alcohol ( $\text{R} = \text{CH}_2\text{OH}$ ) was carried out in the presence of a base ( $\text{Et}_3\text{N}$ , 5 mol %), the yield and ratio of products did not change appreciably. This indicates the absence of nucleophilic attack in the catalytic cycle.

The system under study illustrates the possibility for tuning the direction of catalytic process through variation of fine balance of particular elementary stages. Now, we are continuing studies of the detailed

reaction mechanism for different catalysts, as well as of the effect of substituents in the alkyne molecule on the product yield and ratio.

### EXPERIMENTAL

Benzeneselenol was synthesized by the procedure described in [19]. The alkynes were commercial products (from Aldrich and Acros); their purity was checked by spectral methods ( $^1\text{H}$  and  $^{13}\text{C}$  NMR) prior to use.

**NMR experiments.** The NMR spectra were recorded on a Bruker DRX-500 spectrometer at 500 and 95 MHz for  $^1\text{H}$  and  $^{77}\text{Se}$ , respectively. The chemical shifts of protons were measured relative to residual proton signals of the solvents; the  $^{77}\text{Se}$  chemical shifts were measured relative to  $\text{Se}_2\text{Ph}_2/\text{CDCl}_3$  as external reference ( $\delta_{\text{Se}}$  463.0 ppm) [20]. All two-dimensional spectra were processed on Silicon Graphics workstation using XWINNMR software package [version 2.0, © 1998 Bruker Analytik GmbH]. The following pulse sequences were applied: NOESY [21], LR-COSY [22], HMQC [23, 24]. The parameters for data acquisition and processing were the same as in [25]. In LR-COSY experiments, the delay for evolution of spin-spin coupling was set at 0.5 s. In NOESY experiments, the mixing period was 0.8–1.2 s (it was optimized according to the results of inversion-reduction procedure [25]). To increase the sensitivity of heteronuclear experiments, the magnetization transfer path was selected using pulse field gradients [25]. All measurements were performed at room temperature.

**Catalytic reaction.** Benzeneselenol, 15.7 mg (0.10 mmol), was dissolved under argon in 1 ml of toluene, and 0.15 mmol of appropriate alkyne and 5.8 mg (5 mol %) of  $\text{Pd}(\text{PPh}_3)_4$  were added. The resulting solution was heated for 13 h at 80°C. When the reaction was complete, the mixture was evaporated on a rotary evaporator and extracted with 0.5 ml of chloroform-*d*.

**Noncatalytic reaction.** The procedure was the same as above, but no catalyst was added.

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