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# Palladium(II)-catalyzed Amination of Isoprene with Aniline

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**Abstract** — The reaction of isoprene with aniline, catalyzed by the $Pd(acac)_2$–$(RO)_3P$–$CF_3CO_2H$ system, 1 : 4 : 4 [R = Me, Et; acac = $(CH_3CO)_2CH$], in MeCN provides *N*-(3-methylbut-2-en-1-yl)aniline with a high selectivity (up to 84%) and a nearly quantitative yield (75%). At 1 : 4 : 20 and 1 : 4 : 40 molar component ratios in the catalytic system, up to 28–31% of *N*,*N*-(2,3-dimethylprop-2-en-1-yl)aniline is formed. Telomeric reaction products appear at 1 : 2 : 4 and 1 : 1 : 10 ratios.

Allylamines are used in organic chemistry as basic building blocks for complex organic molecules. The can serve as starting materials in the synthesis of such compounds as α- and β-amino acids, alkaloids, or carbohydrates. One of the most perspective and convenient synthetic approaches to allylamines involves direct amination of 1,3-dienes, catalyzed by complexes of transition metals of the Ni triad. Depending of the nature of the catalytic system, hydroamination of 1,3-dienes is accompanied by their telomerization. Palladium(II) and palladium(0) complexes frequently give 2:1 telomerization products. As shown in [1–7], the [Pd] : [P] molar ratio of 1 : 4 in the $Pd(acac)_2$–$(BuO)_3P$ catalytic system is optimal for telomerization of isoprene (**I**) with various amines in MeCN. With mono- and dialkylamines and with isoprene as 1,3-diene, acid additives in a catalytic system containing palladium(II) diacetylacetonate (acac) complexes and P(III) ligands allow one to control the regioselectivity of telomer formation [1–3]. With strong acids, such as $BF_3 \cdot OEt_2$, *N*-(3,6-dimethylocta-2,7-dien-1-yl)dialkylamines are formed highly selectively [1]. Evidence for the suggestion that in the presence of noncoordinating acids cationic Pd(II) complexes are formed, that are responsible for the formation of telomers like **II**, was obtained in [4, 5]; therewith, compounds **II** formed with a selectivity of up to 96%. In the presence of coordinating acids, by varying the composition of catalytic system **A** [$PdX_2$–$R_3P$–HX, where HX is acid] one can prepare telomers with a natural 2,6-dimethyloctane skeleton, specifically, α-geranyldialkylamines, with a selectivity of up to 40% [2]. The reactions of isoprene with aromatic amines, unlike those with aliphatic amines, in the presence of catalytic system **A** provide isoprene hydroamination products (adducts) [6–8]. Components for catalytic system **A** were found, that allowed *N*-(3-methylbut-2-en-1-yl)aniline (**III**) and methylaniline (**IV**) to be prepared with a selectivity of 78–95% [6–8], and, therewith, the yield of telomers was no higher than 5–6%. We studied the reaction of isoprene with aniline, catalyzed by system **B** [$Pd(acac)_2$–$(RO)_3$–$CF_3CO_2H$, where R = Me, Et] in MeCN, aiming at preparing synthetically useful isomeric adducts other than amine **III**, such as *N*-(1,2-dimethylprop-2-en-1-yl)aniline (**V**), *N*-(1,1-dimethylprop-2-en-1-yl)-aniline (**VI**), and *N*-(2-methylbut-2-en-1-yl)aniline (**VII**), as well as exploring the possibility of formation of telomers **VIII**–**XI** (the reactions were performed in sealed glass ampules 25 ml in volume). The resulting data are presented in the table.

As shown in [7], the reaction of isoprene with $PhNH_2$ in the presence of the $Pd(acac)_2$–$(BuO)_3P$–$CF_3CO_2H$ catalytic system (component molar ratio 1 : 4 : 10) gives adduct **III** with a selectivity of 78%. We found that with less bulky phosphites as components of the catalytic system, adduct **III** is formed with a higher selectivity (86%), and the total yield of adducts is 25% (see table). As seen from data in the table and in [7], at the 1 : 4 : 10 component molar ratio in system **B**, the major reaction product is adduct **III** with any phosphite. Longer heating of the reaction mixture (87 instead of 32 h) renders the formation of adduct **III** less selective. At the 1 : 4 : 4 molar component ratio in system **B**, adduct **III** is formed with a high selectivity (up to 84%; yield 75%). Increased fraction of acid in system **B** (1 : 4 : 20 and 1 : 4 : 40) adversely affects the selectivity of adduct **III** formation; therewith, more adducts **V**–**VII** are formed, and the selectivity of adduct **VII** formation increases to 28–31%. With less phosphorus ligand, the selectivity of adduct formation changes and the spectrum of reaction products widens to include telomers. Telomers appeared in the reaction mixture in the presence of catalytic system **B** with the 1 : 2 : 4 component ratio

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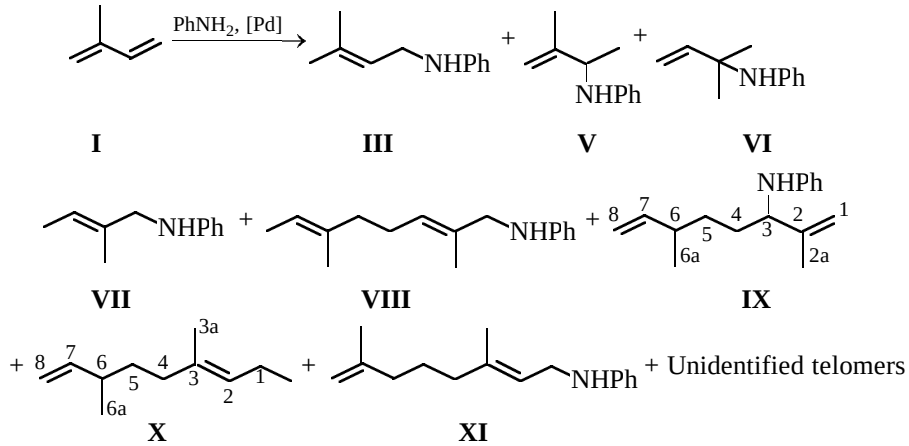
Composition of products of the reaction of isoprene with $PhNH_2$ in the presence of the $Pd(acac)_2$–$(RO)_3$–$CF_3CO_2H$ catalytic system in MeCN [$Pd(acac)_2$ 0.5 mol%, isoprene : $PhNH_2$ = 2 : 1, 25 ml of MeCN per 0.2 mol of $PhNH_2$, 100°C]

| Component molar ratio in the catalytic system | R | τ, h | Yield, % | | | Composition of adducts, % | | | | | | Composition of telomers, % | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | dimers | adducts | telomers | **III** | **V** | **VI** | **VII** | **V + VII** | **III + VI** | **VIII** | **IX** | **X** | **XI** | Unidentified products |
| 1:4:4 | Me | 32 | 0.9 | 75 | – | 84 | 9 | 1 | 5 | 14 | 85 | – | – | – | – | – |
| | Et | 32 | – | 62 | – | 89 | 5 | 2 | 4 | 9 | 91 | – | – | – | – | – |
| 1:4:10 | Me | 32 | 13 | 25 | – | 86 | 4 | – | 10 | 14 | 86 | – | – | – | – | – |
| | Et | 32 | 6 | 59 | – | 65 | 15 | 8 | 13 | 28 | 73 | – | – | – | – | – |
| | Et | 87 | 2 | 34 | – | 50 | 23 | 10 | 17 | 40 | 60 | – | – | – | – | – |
| 1:4:20 | Me | 32 | 30 | 40 | – | 61 | 17 | 5 | 17 | 34 | 66 | – | – | – | – | – |
| | Et | 32 | 2 | 33 | – | 44 | 16 | 9 | 31 | 47 | 53 | – | – | – | – | – |
| 1:4:40 | Et | 32 | 16 | 30 | – | 30 | 17 | 25 | 28 | 45 | 55 | – | – | – | – | – |
| 1:2:4 | Me[a] | 168 | 2 | 5 | 24 | 40 | 12 | 6 | 42 | 54 | 46 | 9 | 20 | 42 | – | 18 |
| | Et[a] | 168 | 14 (3[b]) | 8 | 25 | 55 | 22 | 4 | 19 | 41 | 59 | 10 | 23 | 40 | – | 17 |
| | Et | 32 | 13 (0.1[b]) | 36 | 31 | 53 | 20 | 5 | 22 | 42 | 58 | 7 | 25 | 47 | 4 | 17 |
| 1:2:10 | Et | 32 | – | 85 | Traces | 51 | 14 | 9 | 26 | 40 | 60 | – | – | – | – | – |
| 1:1:1 | Me | 34 | – | 5 | 5 | 23 | 28 | 6 | 43 | 71 | 29 | – | – | – | – | – |
| | Et | 31 | – | 26 | 46 | 34 | 31 | 9 | 26 | 57 | 43 | 7 | 26 | 49 | 5 | 13 |
| | Et | 82 | – | 55 | 16 | 22 | 31 | 10 | 37 | 68 | 32 | 8 | 22 | 48 | 3 | 19 |
| 1:1:4 | Me | 37 | 6 | 40 | 14 | 37 | 26 | 2 | 35 | 61 | 39 | 8 | 27 | 47 | 2 | 16 |
| | Et | 85 | 7 | 66 | 13 | 18 | 15 | 10 | 57 | 46 | 53 | 11 | 26 | 45 | 3 | 15 |
| 1:1:10 | Me | 37 | 7 | 4 | – | 14 | 19 | 11 | 42 | 21 | 68 | – | – | – | – | – |
| | Et | 32 | 24 (0.01[b]) | 30 | 15 | 56 | 18 | 1 | 25 | 43 | 57 | 13 | 25 | 43 | 8 | 11 |
| 1:0:10 | Et | 32 | – | 28 | – | 50 | 20 | 10 | 21 | 40 | 60 | – | – | – | – | – |

[a] The reaction was performed at 20°C. [b] Hydrogenated isoprene dimers ($M^+$ 138).




**I** **III** **V** **VI**

**VII** **VIII** **IX**

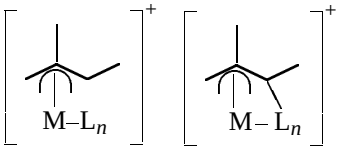
**X** **XI**

at 20°C; therewith, the adduct fraction contained up to 38% of compounds **V** + **VII**; heating of the reaction mixture at 100°C increases the yield of adducts and telomers with no essential effect on selectivity. It should be noted that we are the first to obtain telomeric products by the reaction of isoprene with aniline in the presence of a catalytic system like **A**, and telomers **IX** and **X** are the most abundant. In the latter fraction, unidentified components with $M^+$ 229 were found, that, as judged from the GC retention time, are

likely to be telomers with the main hydrocarbon chain no shorter than $C^8$. Excess acid (1 : 2 : 10 component molar ratio in catalytic system **B**) only slightly affects the selectivity of adduct formation and fully suppresses telomer formation.

With catalytic system **B** with [Pd] : [P] = 1 : 1, too, telomers are formed, isomers **IX** and **X** being the most abundant, and the selectivity of adduct **V** formation is up to 31%; excess acid (1 : 1 : 10 component molar ratio in system **B**) does not exclude telomer formation. Among adducts, adducts **V** and **VII** are formed much more selectively. From the preparative viewpoint, adduct **V** that has an asymmetric center is the most interesting, and, moreover, it has the lowest boiling point among the adducts formed and is easily isolable from the reaction mixture by distillation. Isomer **VI** is always the minor component, apparently, because of the steric hindrances associated with the formation of a quaternary carbon center. If the catalytic system comprises no phosphorus ligand, i.e. when the reaction is performed in the presence of $Pd(acac)_2$–$CF_3CO_2H$, the conversion of isoprene is low, but adduct **III** still remains the major product, and telomers are not formed at all.

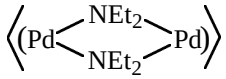
Previously the effect of protic and aprotic acids on the regioselectivity of palladium-catalyzed reactions of isoprene with amines was discussed in [1, 4]. According to [9, 10], cationic nickel complexes **XII** with a $\eta^3$-1,2-dimethylallyl ligand is 5 times thermodynamically more favorable than cationic nickel complexes **XIII** with a $\eta^3$-1,1- dimethylallyl ligand. On this basis, it was suggested [1, 4] that it is the formation of cationic π-allyl palladium complexes that is responsible for the alteration of regioselectivity in the presence of acids.




**XII** **XIII**

**V** **VII** **III** **VI**

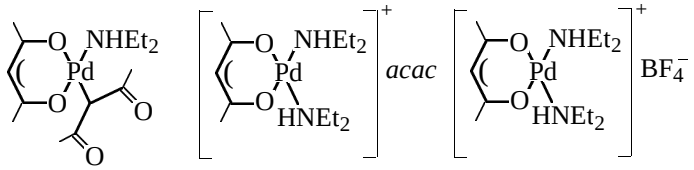
Comparison of our data on reaction of diene **I** with $PhNH_2$ with data in [1, 11, 12] on telomerization of isoprene with $Et_2NH$ allows us to reveal a considerable effect the nature of the amine exerts on the reaction result. Thus, for example, Keim *et al*. [1] reported on a direct relation between the yield of adducts and the quantity of phosphorus ligand in the catalytic system in the telomerization of isoprene with $Et_2NH$ in the presence of $Pd(acac)_2$–$R_3P$–$BF_3 \cdot OEt_2$. The higher the [P] : [Pd] molar ratio at an invariable acid fraction {[Pd] : [$BF_3 \cdot OEt_2$] = 1 : 10}, the higher the yield of adducts, and at [P] : [Pd] = 1 : 1 under the same conditions, telomers are already formed with a selectivity of 95%. As the quantity of acid is decreased at [P] : [Pd] : [$BF_3 \cdot OEt_3$] = 1 : 1 : 1(2), the conversion of isoprene is decreased to 2%, whereas in our case the same catalytic system in the reaction with $PhNH_2$ provides a quantitative yield of adducts. Apparently, such a substantial difference in the reactions of isoprene with $Et_2NH$ or $PhNH_2$ in the presence of similar catalytic systems is associated with different coordinating powers of the amines and gives indirect evidence showing that amines take part not only in the stage involving attack of palladium-coordinated isoprene, but also in early stages of the catalytic cycle, responsible for the mode and selectivity of coordination of the 1,3-diene. The first evidence for the involvement of π-allyl palladium complexes containing an amide ligand in telomer formation in the reaction of isoprene with $Et_2NH$ has been obtained in [13]. Amide palladium complex **XIV** formed by the reaction of bis(π-allyl)palladium with $Et_2NH$ can catalyze telomerization of butadiene with $Et_2NH$ in the presence of $Ph_3P$. In the absence of butadiene, complex **XIV** reacts nether with $Et_2NH$ nor with $Ph_3P$.




**XIV**

Later on it was found that the $Pd(acac)_2$–$BF_3 \cdot OEt_2$ catalytic system can catalyze the telomerization of 1,3-butadiene with aliphatic secondary amines, resulting in 78–99% yields of telomers; with the same catalytic system in the absence of amines, no other products than polymers are formed [14]. The IR and UV spectra of products of the reaction in the $Pd(acac)_2$–$BF_3 \cdot OEt_2$–$C_4H_6$ system were studied, and the structure the palladium hydride complex $[(C_4H_6)_nPdH]BF_4$ that is catalytically active in telomerization was proposed on this basis. It was believed that nucleophile is involved exclusively in the final stage of the catalytic cycle, namely, in the stage of insertion of secondary amine into the bond of 1,3-butadiene with the palladium metal center [14]. However, comparison of the results of isoprene telomerization with primary [3] and secondary aliphatic amines [1, 2, 12, 15] led to a suggestion that the coordination complexes of $Pd(acac)_2$ with amine and phosphorus ligands, like complexes **XV**–**XVII**, are involved in formation of catalytically active centers [3].

Later on this suggestion was confirmed by Chernyshev *et al*. [16] who studied the $^1H$ and IR spectra




**XV** **XVI** **XVII**

of products of the reaction of $Pd(acac)_2$–$BF_3 \cdot OEt_3$ with $Et_2NH$, as well as the telomerization of 1,3-butadiene with secondary amines in the presence of the $Pd(acac)_2$–$BF_3 \cdot OEt_2$ catalytic system. Previously complexes **XV** and **XVI** were described in [17, 18]. Chernyshev *et al.* [19] proposed a scheme for the formation of complex **XVII** that as actively catalyzed telomerization of dienes with secondary amines as $Pd(acac)_2$–$BF_3 \cdot OEt_2$, which made the referees to conclude that complex **XVII** is a precursor of the active complex $[L_m–Pd–H]^+BF_4^-$ formed *in situ*. It was also mentioned in [19] that the formation of the latter complex is complete before telomerization commences, and its concentration does not vary throughout the reaction. In the present work we also showed that diene **I** can react with $PhNH_2$ in the absence of phosphorus ligand, i.e. in the presence of the $Pd(acac)_2$–$CF_3CO_2H$ catalytic system. Moreover, we obtained indirect evidence for the involvement of palladium hydride complexes in the catalytic cycle. GC-MS analysis of products of the reaction in the presence of system **B** with 1:2:4 and 1:1:10 components molar ratios revealed hydrogenated isoprene dimers with $M^+$ 138, along with isoprene dimers with $M^+$ 136, adducts **III** and **V**–**VII**, and telomers **VIII**–**XI**. The presence of hydrogenated isomer dimers can be explained by the fact that cationic palladium(II) hydride complexes can catalyze hydrogen transfer from alcohols and amines to the double bonds in unsaturated hydrocarbons (see, for example, [20]). In the presence of acids, the possibility of formation of cationic π-allyl complexes depends on a number of conditions, acid concentration inclusive. However, analysis of the isomeric composition of the adducts and telomers shows that in the presence of a larger quantity of acid (for example, at the 1:4:20 molar component ratio insystem **B**), when formation of cationic complexes is the most probable, the yields of adducts formed from cationic complex **XII** do not increase (see table). Apparently, in the reaction of isoprene with $PhNH_2$ in the presence of catalytic system **B**, unlike the reaction with aliphatic amines, intermediate complexes **XII** and **XIII** are unlikely to be formed.

## EXPERIMENTAL

Gas chromatography–mass spectrometry was performed on an Analytical VG-7070E instrument at 70 eV and an ion source temperature of 150°C. The $^1H$ NMR spectra were on Bruker WR-200SY and Bruker AMX-400 instruments ($CDCl_3$, internal reference TMS).

Gas chromatography was performed on a Finnigan-9001 chromatograph with a capillary column (*l* 30 m, stationary phase DB 5.625, temperature programming from 50 to 200°C at a rate of 8 deg $min^{-1}$ and from 200 to 310°C at a rate of 12 deg $min^{-1}$); the reference was $C_{21}H_{44}$. The isomeric composition of **VIII**–**XI** was assessed on the basis of retention times [7].

Monomers of 99% purity were used in the work. Isoprene and aniline were distilled over KOH before use.

**Reaction of isoprene with aniline in MeCN.** A glass ampule was charged under argon with 1 mmol of $Pd(acac)_2$, 0, 1, 2, or 4 mmol of $(EtO)_3P$ or 1, 2, or 4 mmol of $(MeO)_3P$, 25 ml of MeCN, 400 mmol of isoprene, 200 mmol of aniline, and 1, 2, 4, 10, or 20 mmol of $CF_3CO_2H$. The ampule was sealed and left to stand at 20°C (see table). Low-boiling reaction products were removed in a vacuum, and the residue was distilled collecting a fraction boiling at 40–170°C (2 mm Hg), that was analyzed by GC and GC–MS. The $^1H$ NMR spectra of isomers **III**, **V**, **VII**, **VIII**, and **XI** were published in [7].

**Adduct VI.** $^1H$ NMR spectrum, δ, ppm: 1.16 s and 1.21 s (6H, $2CH_3$), 4.69–5.00 m (2H, $CH_2$=), 5.17–5.43 m (1H, CH=), 6.61 m (3H, Ph), 7.14 m (2H, Ph). Mass spectrum, *m/z* (*I*, %): 161 ($M^+$ 67), 146 (92), 120 (96), 118 (16), 93 (40), 77 (25).

**Telomer IX.** $^1H$ NMR spectrum, δ, ppm: 0.97 d (3H, $C^{6a}H^3$, *J* 6.54 Hz), 1.35–1.49 m (4H, $C^4H_2$, $C^5H_2$), 2.01–2.14 m (3H, $C^6H$), 1.66 s (3H, $C^{2a}H^3$), 3.89 t (2H, $C^3H$, *J* 6.03 Hz), 4.84–5.92 m (1H, $C^7H$, $J_{trans}$ 18.06, $J_{cis}$ 9.66, $J_{gem}$ 1.5 Hz), 4.92 s and 4.95 s (2H, $C^1H_2$), 5.62–5.72 m ($J_{trans}$ 18.06, $J_{cis}$ 9.66, $J_{7–6}$ 7.48 Hz), 6.58–6.77 m (3H, Ph), 7.13–7.23 m (2H, Ph). Mass spectrum, *m/z* (*I*, %): 229 ($M^+$ 12), 172 (8), 146 (10), 93 (100), 81 (15), 77 (14).

**Telomer X.** $^1$H NMR spectrum, δ, ppm: 1.00 d (3H, $C^{6a}H^3$, *J* 6.54 Hz), 1.26–1.49 m (2H, $C^5H_2$), 1.70 s (3H, $C^{3a}H^3$), 1.93–2.14 m (3H, $C^6H$, $C^4H_2$), 3.71 d (2H, $C^1H_2$, *J* 6.56 Hz), 4.98–5.01 m (1H, $C^7H$, $J_{trans}$ 17.75, $J_{cis}$ 12.14, $J_{gem}$ 0.9 Hz), 5.33 t (1H, $C^2H$, *J* 6.56 Hz), 5.65–5.75 m ($J_{trans}$ 17.75, $J_{cis}$ 12.14, $J_{7–6}$ 8.25 Hz), 6.58–6.77 m (3H, Ph), 7.13–7.23 m (2H, Ph). Mass spectrum, *m/z* (*I*, %): 229 ($M^+$ 28), 172 (5), 146 (16), 93 (100), 81 (22), 77 (12).

## ACKNOWLEDGMENTS

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