

# Addition of tetrachloromethane to alkenes catalyzed by copper(I) complexes with *N*-thioacylamidothiophosphate ligands

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## Abstract

The catalytic activity of copper(I) complexes with *N*-thioacylamidothiophosphate ligands towards addition reaction of tetrachloromethane to alkenes was investigated. The influence of nucleophilic co-catalysts (alcohols, *N*-heterocycles, etc.) on catalytic activity of metal complexes was determined.

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**Keywords:** Kharasch reaction; Homogeneous catalysis; Copper(I) complexes

## 1. Introduction

The addition of polyhalogenated alkanes to carbon–carbon double bonds (Kharasch reaction [1]) is one method of forming C–C bonds and it has been applied to the synthesis of polyfunctional acyclic and heterocyclic compounds ( $\beta$ -aminoacids [2], alkaloids [3] and others).

This reaction has been of interest during the last 50–60 years. Primarily organic peroxides were used as initiators for this process. However, in the presence of free-radical initiators not only adduct 1:1, but also different telomerhomologues are obtained [4]. Exploration of the catalytic activity of metal complexes in the Kharasch process has increased the sphere of synthetic application of this reaction. In the presence of metal complexes, it is possible for the reaction to proceed in mild conditions, and to significantly increase the selectivity of the process.

Intense interest in copper complexes applied in the Kharasch reaction and related processes is connected with its attractive activity/cost ratio [5,6]. The analysis of literature data shows that a restricted range of copper catalysts was investigated previously

in this process, and in most cases an excess of polyhalogenated alkane (i.e. five-fold) was needed to achieve a good yield of the target product.

This work is devoted to the investigation of the catalytic activity of copper(I) complexes with *N*-thioacylamidothiophosphate ligands [7–9] applied to the addition reaction of CCl<sub>4</sub> to alkenes.

## 2. Results and discussion

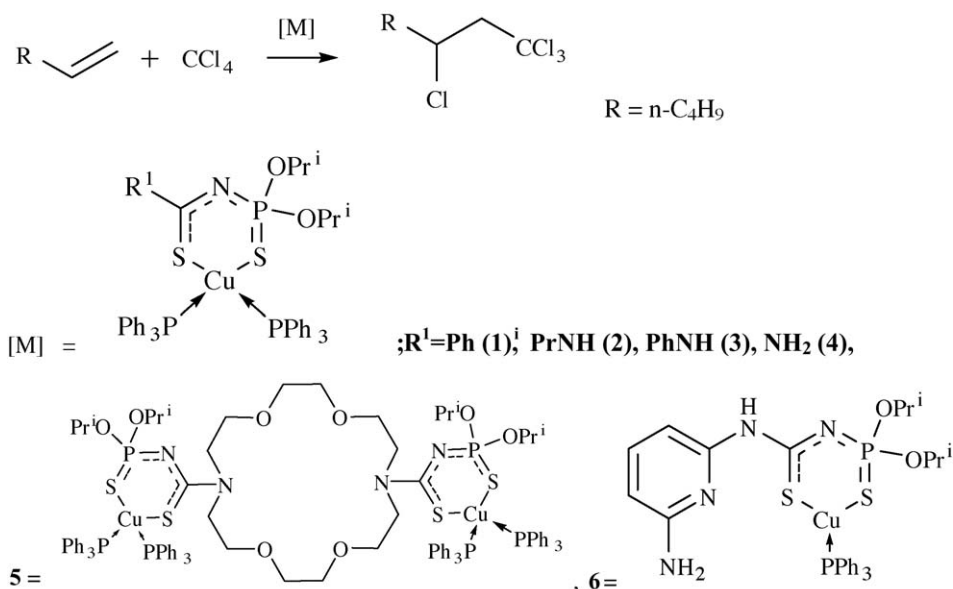
### 2.1. Addition of tetrachloromethane to 1-hexene in the presence of mononuclear copper(I) complexes

The addition of tetrachloromethane to 1-hexene was taken as a model (Scheme 1). We have found that copper(I) complexes with *N*-thioacylamidothiophosphate ligands can catalyze the process to give 1,1,1,3-tetrachloroheptane as a main product. Catalytic activity of the complexes is represented in Table 1 (the conversion of 1-hexene was less than 1% when the initial rate was determined; the rate of the non-catalyzed reaction  $(1.8 \pm 0.13) \times 10^{-8} \text{ mol l}^{-1} \text{ s}^{-1}$  is three orders of magnitude lower than in the presence of catalyst, so the influence of non-catalyzed reactions for the further kinetic measurement was neglected). As follows from Table 1, the composition and structure of the ligand has a major influence on the catalytic activity. Previously [10] it was suggested that there is no correlation between donating ability of phosphine ligands ( $\text{P}(p\text{-CF}_3\text{C}_6\text{H}_4)_3$ ,

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Scheme 1.

$P(C_6H_5)_3$ ,  $P(p-CH_3OC_6H_4)_3$ ) and catalytic activity of ruthenium(II) complexes with these ligands in the Kharasch reaction. In our case, to a first approximation it is possible to conclude that  $\sigma$  or  $\pi$  acceptor substituents  $R^1$  in the ligands (Scheme 1) promote the reaction.

High chemoselectivity was illustrated by the investigated copper(I) complexes. The amount of by-products (products of 1-hexene isomerization and products of metathesis of alkene's C–H bonds and  $CCl_4$  C–Cl bonds) is two orders of magnitude lower in comparison with main product of  $CCl_4$  addition. Thus, the rate of 3-chlorohex-1-ene formation in the presence of **1** is  $9 \times 10^{-8} \text{ mol l}^{-1} \text{ s}^{-1}$  which is two orders of magnitude lower than the rate of 1,1,1,3-tetrachloroheptane formation (Table 1) and only traces of 2-hexene and 3-hexene were determined according to the GC–MS data.

We also investigated stereoselectivity of the reaction of  $CCl_4$  addition to cyclohexene in the presence of complexes **1–6**. Stereoselectivity appeared to be low in this case. According to GC–MS data *cis*- and *trans*-isomers of 2-trichloromethyl-1-chlorocyclohexane are obtained in equal quantity. Only in the presence of bulky complex **5**, the quantity of the *trans*-isomer appeared to be more than *cis*-isomer (*trans*:*cis* = 1.4:1).

Table 1  
Rate constants, initial rates  $W_0$  of  $CCl_4$  to 1-hexene addition and yields 1,1,1,3-tetrachloroheptane in the presence of mononuclear Cu(I) complexes

| Catalyst | $k \times 10^{-4}$ ( $l^3 \text{ s}^{-1} \text{ mol}^{-3}$ ) | $W_0 \times 10^{5a}$ ( $\text{mol l}^{-1} \text{ s}^{-1}$ ) | Yield <sup>b</sup> (%) |
|----------|--|---|------------------------|
| <b>1</b> | $1.3 \pm 0.09$   | $0.55 \pm 0.04$   | 32                     |
| <b>2</b> | $6.4 \pm 0.4$  | $2.7 \pm 0.19$  | 24                     |
| <b>3</b> | $9.3 \pm 0.65$   | $3.9 \pm 0.3$   | 36                     |
| <b>4</b> | $3.3 \pm 0.2$  | $1.4 \pm 0.09$  | 37                     |
| <b>5</b> | $11.9 \pm 0.8$   | $5.0 \pm 0.35$  | 57                     |
| <b>6</b> | $20.7 \pm 1.4$   | $8.7 \pm 0.6$   | 41                     |

<sup>a</sup> Complexes are stable during the experiment.

<sup>b</sup> Yield of 1,1,1,3-tetrachloroheptane without catalyst is 0.5%;  $T = 120^\circ \text{C}$ ; 10.5 h.

The synthetically important result was achieved: the yield of 1,1,1,3-tetrachloroheptane in the presence of complexes **1** and **5** and using addition of potassium carbonate at  $120^\circ \text{C}$ , 10.5 h, was 90%. It is important that this result was obtained using substrates with non-activated carbon–carbon double bonds (e.g., 1-hexene) and without increasing the concentration of tetrachloromethane and catalyst. Usually in such a case, 5–10 mol excess of  $CCl_4$  to alkene [11] is used and higher amount of catalysts [12] – several mole percent (to alkene) – in comparison to 0.1 mol% in our catalytic system.

In order to investigate the reaction mechanism, we have measured orders on the reagents. It was found that the reaction rate is second order on tetrachloromethane concentration, first order on 1-hexene and first order on metal complex concentration. Addition of benzoquinone or iodine inhibits the reaction, suggesting a radical nature of the reaction.

The data obtained on reaction orders suggests for our reaction the mechanism is close to the mechanism of redox-catalysis, where the metal complex takes part in trichloromethyl radical formation with a regeneration at the chain transfer stage. The mechanism of redox-catalysis is typical for the range of Kharasch addition reactions in the presence of transition metal complexes [12,13].

In the case of the redox mechanism of catalysis it should be first order on metal complex [13], and it is in agreement with the obtained kinetic data in our case. Second order on tetrachloromethane, mentioned previously [14], may be explained by the following way: it was determined that decreasing tetrachloromethane concentration follows with an increasing amount of by-products (in comparison to the main product). The loss of the reaction selectivity at low concentrations of tetrachloromethane can lead to the overvaluation of  $CCl_4$  order.

The mechanism of redox catalysis assumes zero order on alkene concentration. The first order on alkene concentration obtained in our case can be justified on the basis of 1-hexene participation in the formation of active form of the catalyst (copper

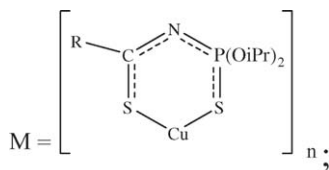


Fig. 1. R = Ph (**7**), 4'-aminobenzo-15-crown-5 (**8**), 1-aminonaphthyl (**9**), PhNH (**10**), *N*-2,6-diaminopyridine (**11**), morpholine-1-yl (**12**), piperidine-1-yl (**13**), *N'*-phenylhydrazino (**14**), NH<sub>2</sub> (**15**).

complexes with alkene ligands are known [15]). For the ruthenium(II) catalyzed Kharasch addition reaction, the mechanism which takes into account alkene participation in the formation of active form of the catalyst was suggested earlier [16].

An additional argument in support of the redox mechanism could be formation of hexachloroethane – the product of trichloromethyl radical dimerization – in the reaction mixture. Hexachloroethane was not detected in the reaction mixture in the presence of hexene. We supposed that trichloromethyl radical forms in the reaction mixture, but readily reacts with 1-hexene. So we tried to detect C<sub>2</sub>Cl<sub>6</sub> when 1-hexene was excluded from the reaction mixture. Indeed, C<sub>2</sub>Cl<sub>6</sub> was detected in these conditions by means of GC–MS method.

Additional information on reaction mechanism was expected to be obtained by analyzing of the EPR spectra of the reaction mixtures. However, in the anaerobic conditions no signal was detected which we could refer to the formation of copper(II). The absence of copper(II) signal in EPR spectra was described and interpreted previously [17].

## 2.2. Polynuclear copper(I) complexes with *N*-thioacylamidothiophosphate ligands as catalysts for the addition reaction of tetrachloromethane to 1-hexene

We have investigated a range (Fig. 1) of polynuclear copper(I) complexes with *N*-thioacylamidothiophosphate ligands in the addition reaction of tetrachloromethane to 1-hexene. This group of catalysts has common features with mononuclear copper(I) complexes **1–6** and also significant differences in behavior.

Complexes **7–15** show moderate catalytic activity (Table 2) in the addition reaction between tetrachloromethane and 1-hexene (to give 1,1,1,3-tetrachloroheptane as a main product). The

Table 2  
Reaction rate constants, initial rates  $W_0$  of CCl<sub>4</sub> to 1-hexene addition and yield of 1,1,1,3-tetrachloroheptane in the presence of polynuclear Cu(I) complexes

| Catalyst  | $k$ (l s <sup>-1</sup> mol <sup>-1</sup> ) | $W_0 \times 10^{5a}$ (mol l <sup>-1</sup> s <sup>-1</sup> ) | Yield <sup>b</sup> (%) |
|-----------|--|---|------------------------|
| <b>7</b>  | 0.7 ± 0.05                                 | 1.5 ± 0.1   | 23                     |
| <b>8</b>  | 1.4 ± 0.1                                  | 2.9 ± 0.2   | 54                     |
| <b>9</b>  | 0.6 ± 0.04                                 | 1.3 ± 0.09  | 17                     |
| <b>10</b> | 0.6 ± 0.04                                 | 1.3 ± 0.09  | 32                     |
| <b>11</b> | 1.19 ± 0.08                                | 2.5 ± 0.18  | 34                     |
| <b>12</b> | 1.24 ± 0.09                                | 2.6 ± 0.18  | 6                      |
| <b>13</b> | 1.38 ± 0.1                                 | 2.9 ± 0.2   | 12                     |
| <b>14</b> | 1.8 ± 0.13                                 | 3.7 ± 0.26  | 24                     |
| <b>15</b> | 1.5 ± 0.11                                 | 3.1 ± 0.22  | 23                     |

<sup>a</sup> Complexes are stable during the experiment.

<sup>b</sup> Reaction conditions:  $T = 120^\circ\text{C}$  and 10.5 h.

Table 3

Initial rates  $W_0$  of CCl<sub>4</sub> to 1-hexene addition in the presence of polynuclear Cu(I) complexes and nucleophiles (mole ratio CCl<sub>4</sub>:1-hexene:nucleophile = 1.3:1:1.3)

| Copper(I) complex | Nucleophile          | $W_0 \times 10^5$ (mol l <sup>-1</sup> s <sup>-1</sup> ) | $\beta$ |
|-------------------|----------------------|--|---------|
| <b>7</b>          | –                    | 1.5 ± 0.1  | –       |
|                   | THF                  | 2.1 ± 0.15   | 0.48    |
|                   | Acetonitrile         | 1.9 ± 0.13   | 0.33    |
|                   | Methanol             | 15.4 ± 1.08  | 0.47    |
|                   | 2,5-Dimethylpyridine | 293.8 ± 20.6   | 0.62    |
| <b>11</b>         | –                    | 2.5 ± 0.18   | –       |
|                   | Ethanol              | 24.2 ± 1.7   | 0.48    |
|                   | Methanol             | 24.4 ± 1.7   | 0.47    |
|                   | THF                  | 3.4 ± 0.2  | 0.48    |
|                   | Pyridine             | 60.2 ± 4.2   | 0.52    |
|                   | 3-Methylpyridine     | 86.4 ± 6.05  | 0.54    |
|                   | 2-Propanol           | 100.6 ± 7.04   | 0.56    |
|                   | 2,5-Dimethylpyridine | 269.9 ± 18.9   | 0.62    |

selectivity of Kharasch addition in the presence of polynuclear copper(I) complexes is as high as in the presence of mononuclear complexes.

We tried to attain a quantitative yield in Kharasch reaction in mild reaction conditions using polynuclear copper(I) complexes. It is known that the catalytic activity of metal complexes in the reactions followed by homolysis of C–X (X = Cl, Br, I) bond could be increased by using nucleophilic additives (alcohols, amines, etc.) [18]. Considering this fact we investigated the influence of nucleophilic co-solvents (co-catalysts) on the reaction rate in the case of polynuclear complexes **7** and **11**.

As follows from Table 3, the highest initial rate could be achieved in the presence of 2,5-dimethylpyridine as co-catalyst. It was found that in the presence of 2,5-dimethylpyridine the reaction takes place even at room temperature, and at 60 °C the yield of 1,1,1,3-tetrachloroheptane reaches 100% in 10.5 h.

To explain the influence of nucleophiles, we confronted the basicity of co-solvents and the initial rate of the reaction. To estimate the basicity,  $\beta$ -parameter [19] was chosen. This parameter characterizes Brønsted basicity of the solvent. The linear correlation ( $R = 0.98$ ) was found between initial reaction rate as a criteria of catalytic activity and basicity of nucleophiles used (Fig. 2). This kind of correlation has not been described in the literature data previously.

The reaction mixture (with **7**) after addition of the nucleophile was analyzed by <sup>31</sup>P NMR. The peak of free *N*-thioacylamidothiophosphate was found at  $\delta$  54.8 ppm. It is interpreted as evidence of the fact that nucleophiles induce the cleavage of not only metal–metal, but also partly metal–ligand bonds. As a result, the catalytic system consists of mononuclear complexes with *N*-thioacylamidothiophosphate and nucleophilic ligand and complex CuCl<sub>2</sub>L<sub>2</sub> (L = nucleophile). The stoichiometry of the last complex was confirmed by elemental analysis.

It was found that the reaction rate is first order on tetrachloromethane concentration, zero order on 1-hexene and first order on metal complex concentration as in the classic variant of redox catalysis (Scheme 2). Additional evidence to this could be a signal of copper(II) in EPR spectra of the reaction mixture containing complex **12** ( $g_0 = 2.097$ ,  $A_0 = 66.8 \times 10^{-4} \text{ cm}^{-1}$ ).

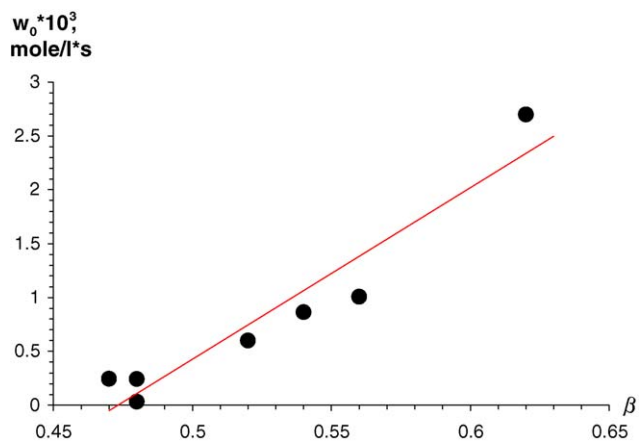
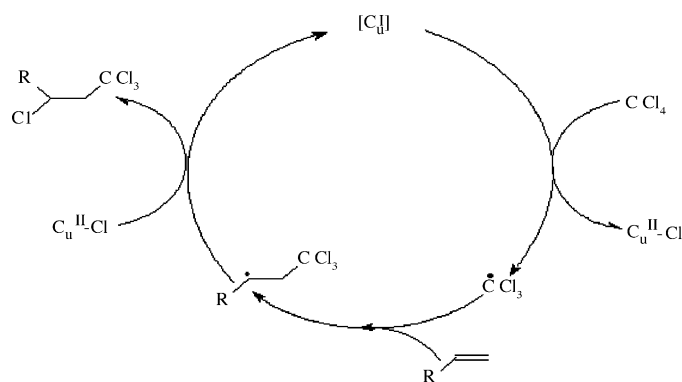


Fig. 2. Correlation between  $W_0$  and basicity of nucleophiles (for the complex **11**).



Scheme 2.

In conclusion, it is important to underline that the two investigated catalytic systems based on poly- and mononuclear complexes with *N*-thioacylamidothiophosphate ligands have common features in their ability to activate C–Cl bonds of tetrachloromethane. The ability of catalytic system polynuclear *N*-thioacylamidothiophosphate copper(I) complex—nucleophile to perform the reaction at mild (room temperature, 60 °C) conditions with non-activated substrate could be promising in application to organic synthesis.

### 3. Experimental

#### 3.1. General

Tetrachloromethane, 1-hexene, cyclohexene, hexane were purified according to the standard procedure [20]. Directly prior to use, alkenes were distilled over sodium. The purity of reagents was measured by GC and GC–MS methods.

CW EPR measurements in solutions were performed on Bruker ESP 300 spectrometer equipped with X-band 4110ST resonator and standard nitrogen flow accessory. The field was controlled by a Bruker ER035 field meter and the microwave frequency measured with a Hewlett-Packard 5255A frequency counter. EPR spectra were recorded in quartz capillary at tem-

perature 303 K. The modulation amplitude was chosen, so as not to affect the EPR line widths and for all experiments, has been set to  $(1-2) \times 10^{-4}$  T.

The NMR spectra were recorded on a Varian Unity-300 spectrometer at 25 °C. Working frequency: 121 MHz for  $^{31}\text{P}$ .  $\text{H}_3\text{PO}_4$  (85%,  $\delta$  0) was used as the external reference for  $^{31}\text{P}$  NMR.

#### 3.2. Standard method of synthesis of copper(I) complexes

Copper(I) complexes **1–6** were obtained as described previously [7].

Copper(I) complexes **7–15** were obtained by the reaction of copper(I) iodide (0.5 mmol) suspension with the potassium salt of *N*-thioacylamidothiophosphate ligand  $[\text{RC}(\text{S})\text{NP}(\text{S})(\text{OPr}^i)_2]\text{K}$  (0.5 mmol) in ethanol. The mixture was stirred for 1 h and the precipitate was filtered off. The resulting solution was evaporated in vacuum until the crystallization began. Obtained crystals were recrystallized from 1:5 mixture of  $\text{CH}_2\text{Cl}_2$  and *n*-hexane.

#### 3.3. Standard procedure for kinetic measurements

A measured amount of catalyst was dissolved in 1 ml of  $\text{CCl}_4$ . In a glass ampoule 0.1 ml of this solution and 0.1 ml of 1-hexene were taken (mole ratio  $\text{CCl}_4$ :1-hexene = 1.3:1). The concentration of metal complex was  $4 \times 10^{-3}$  M in each ampoule. After degassing at 300 Pa ampoules were soldered up and heated at 100 °C. The concentration of the addition reaction product was measured by GC method using *n*-tetradecane as an internal standard. Spectral characteristics and other data for the product of addition of tetrachloromethane to 1-hexene were described previously [21].

GC-analysis was made on CHROM-5 with a prepacked column, 1.0 m, packed with sorbent INERTON-N-Super 0.16–0.20 mm, impregnated with 5% SE-30. Carrier gas—helium, hydrogen-flame ionization detector. Temperature conditions: temperature rise from 50 to 170 °C with a velocity of 10 °C/min with further oven control at 170 °C within 4 min. Sample temperature 250 °C, hydrogen spending 30 ml/min.

The order on catalyst was determined for the complexes **3** and **12** by changing of its concentration from  $5.0 \times 10^{-4}$  to  $4.2 \times 10^{-3}$  M. For  $\text{CCl}_4$  and 1-hexene the order was determined by means of substitution of the reagent with inert solvent (hexane).

#### 3.4. GC–MS analysis

GC–MS analysis was made on Turbo Mass Gold (Perkin-Elmer) spectrometer. Capillary column ( $d = 320 \mu\text{m}$ ) 30 m, liquid phase XLB-5, carrier gas—helium (1.2 ml/min), mass-spectrometric detector (total ion current). Temperature conditions: temperature rise from 50 to 280 °C with a velocity of 7.5 °C/min with further oven control at 280 °C within 2 min. Internal standard was *n*-tetradecane.

Mass-spectrum of 2-trichloromethyl-1-chlorocyclohexane.  $m/z$  ( $I_{\text{rel}}$ , %): 199 (0.5), 163 (19), 143 (2), 129 (12), 115 (7), 94 (12), 81 (51), 67 (79), 53 (100), 49 (20).

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