Catalyzed Beckmann rearrangement of cyclohexanone oxime in heterogeneous liquid/solid system
Part 2: Influence of acid catalysts and organic promoters

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ABSTRACT

The influence of some transition metal oxide promoters in the catalyzed Beckmann rearrangement of cyclohexanone oxime was studied by preparing several heterogeneous $H_2SO_4/M/SiO_2$ catalysts using SiO_2 as support and H_2SO_4 as acid source. A definite effect of each metal has been observed and the best results have been obtained with Cr-, Zr- and Zn-oxides based promoter, which have shown an improved selectivity towards ε-caprolactam formation if compared to the H_2SO_4/SiO_2 catalytic system. Moreover, the influence of some organic promoters on the reaction pathway was investigated. Acetic and trifluoroacetic anhydrides gave the best results, even if only the latter allowed the rearrangement even without solid acid catalysts. The transacetylation of the cyclohexanone oxime by using the acetyl caprolactam, which is the product of rearrangement of the acetyl cyclohexanone oxime, was studied for developing a step wise catalytic cycle. Finally, some preliminary results on a homogeneous organic catalyzed process are reported.

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1. Introduction

The first part of our studies dealt with activity and selectivity of acid supported on various solids on the Beckmann rearrangement of cyclohexanone oxime [1]. Despite of the high rate of the reaction at 253 K, the conversion to ε-caprolactam did not reach the completeness because of a simultaneous fast catalysts deactivation. Using aprotic solvents as reaction media, the leaching of acid phase from the surface of the catalyst was observed only in small extent. The comparison of homogeneous and heterogeneous experiments suggested that the reactions take place at the interface, thus explaining the different behaviors observed between homogeneous and heterogeneous reactions [1]. In these systems, cyclohexanone was observed as a by-product even with catalysts having high protonation ability [1], in contrast with what observed in aqueous solution of strong acids, in which no hydrolysis is observed at high acid concentration (>75 wt.%) [2]. The reason of such a behavior could be related to the complex reactions of oximes in non-aqueous solvent [3–5].

Oximes and oximates are known to be quite efficient ligands in coordination chemistry [6–9] and the chemistry of metal-bonded oximes is of interest in the study of a more favorable reaction pathway for Beckmann rearrangement. The idea of promoting Beckmann rearrangement with a metal-based catalyst is quite old, in fact a metal-promoted Beckmann rearrangement of aldoximes was discovered in the late 19th century together with the isolation of the metal complexes intermediates [10], while the rearrangement of ketoximes by the promotional effect of transition metals was developed a century later. The homogeneous catalytic system described was based on tetrabutylammonium perrhenate and CF_3SO_3H in different polar solvents [11,12]. Hydrolysis of the oximes was observed also in the presence of metals and then the authors, in order to avoid this problem, suggested to add $NH_2OH \cdot HCl$ and to operate in azeotropic distillation conditions. Employing such a procedure ε-caprolactam yield of 84% was reached without cyclohexanone formation [12]. More recently, CF_3SO_3H/Rh complex systems shown to exhibit high activity and selectivity in the rearrangement of different ketoximes [13].

The progress on the Beckmann rearrangement observed in recent years by using organic co-catalysts and promoters directly originates from the early work of Beckmann [14]. The first experiments were carried out, in fact, in the presence of acetic anhydride and hydrochloric acid as catalysts using glacial acetic acid as

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[1] Deceased.

(1)

(2)

(3)

X= H, Electron-withdrawing groups
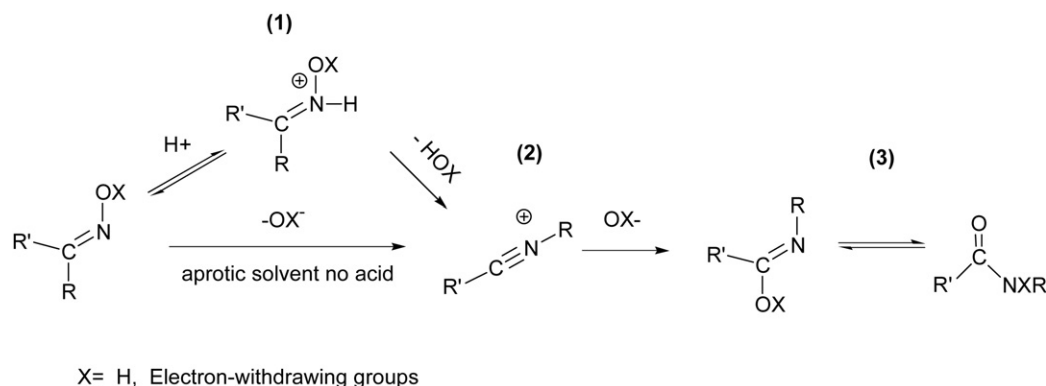
Scheme 1. Rearrangement stages of oximes and oximes derivatives.

solvent (the so called "Beckmann mixture"). In such a media a highly selective conversion to amides was easily achieved [15,4]. As reported by Kuhara almost a century ago, acetyl chloride was employed for the rearrangement and acetyl oxime was recognized to be the active intermediate which, together with the hydrochloric acid, is able to promote the reaction [4].

Later, species like acetyl- and picril-oximes or oxime carbonate, tosylate, sulfonate, etc. were extensively studied by many authors [5,16,17]. Even if the rearrangement of these derivatives occurs with a mechanism similar to that of the oximes, reactions usually happen under milder conditions and, in many cases, without acid catalysts [16,18]. The complex 2,4,6-trichlorotriazine (TCT) with N,N-dimethylformamide reacts with oximes giving in high yield the corresponding amides [19] and recently the catalytic system TCT-ZnCl$_2$ has been recognized to be effective in aromatic oxime rearrangement at 353–373 K in CH$_3$CN [20]. In general, reagents that allow to obtain Beckmann rearrangement of ketoximes at relatively low temperatures presumably convert the oximes to more reactive ether or ester-like intermediates [21]. The compounds, compared to the corresponding oximes, have a lower electronic density on the nitrogen atom and consequently a greater tendency to rearrange even without Brønsted acids [22–24]. As depicted in Scheme 1, the rearrangement of oxime derivatives can follow two different pathways depending on the presence of acid. The protonated oxime (1), which is the starting point for the rearrangement in concentrated mineral acid, is not necessarily involved in aprotic solvent. Nitrilium ion (2) (observed in mineral acid for hindered acetophenone oximes) is a short life intermediate whose formation could be considered the rate determining step of the reaction also in non aqueous solvent [22,25]. The following formation of the imino-amide tautomer (3) by nucleophilic attack of the HOX or OX$^-$ species is generally fast, thus not affecting the kinetics of the whole process [23,25].

In this paper we investigate the influence of organic promoters on the activity and selectivity of the Beckmann rearrangement of cyclohexanone oxime and some N-substituted derivatives catalyzed by solid acids. The effect of different catalysts under different reaction conditions is also reported. Furthermore, some results on homogeneous catalyzed trifluoroacetic acid reactions are also given.

2. Experimental

2.1. Materials

Purified samples of Silica Gel purchased from Grace (90 μm average particle size, BET surface area 364 m^2/g, pore volume 1.14 ml/g,) were obtained by washing the material with aqueous solutions of perchloric acid, then with distilled water. Reagents and solvents were used after purification of the commercially available samples and their purity was checked by the usual methods (melting point, TLC, HPLC, GC and GC–MS). The macro-reticular sulfonated styrene divinyl benzene resins Amberlyst 15^{TM} (BET surface area 36 m^2/g, average pore diameter 21 nm, total pore volume 0.52 ml g^{-1}) was purchased from Aldrich (Amberlyst 15 is a trade mark of Rohm and Haas). Nafion SAC13 fluorosulfonic acid Nafion polymer 10–20% porous nanocomposite on amorphous silica (surface area 200 m^2 g^{-1}, average pore diameter 10 nm, pore volume 0.6 ml g^{-1}) was purchased from Aldrich (Nafion^{TM} is a trade mark of du Pont de Nemours). A treatment of the solvents was carried out in a double bed column, filled with H$_2$SO$_4$/SiO$_2$ and SiO$_2$ to adsorb solvent impurities, which may cause catalyst deactivation. The amount of water was checked following the procedure described in part 1 [26].

2.2. H$_2$SO$_4$/M/SiO$_2$ catalysts preparation

Many catalysts were prepared by wet impregnation (W.I.): a weighted amount of purified silica gel was mixed with a known amount of an aqueous acid solution (10–25%) of the metal precursor of appropriate concentration (Fe$_2$(SO$_4$)$_3$ hydrate, CuSO$_4$ hydrate, Cr$_2$(SO$_4$)$_3$ hydrate, K$_2$CrO$_4$). After 1 h of stirring the surnatant solution was removed by filtration and the wet catalyst was dried in oven for 72 h at 378 K in a stream of N$_2$ and then stored in a dry apparatus (Table 1).

Table 1
H$_2$SO$_4$/M/SiO$_2$ catalysts and their preparation methods

Catalyst	Acids concentration	Metal precursor	Method
SSi10-wi	H$_2$SO$_4$ (10 wt.%)	–	W.I.
SSi20-wi	H$_2$SO$_4$ (20 wt.%)	–	W.I.
SSi25-wi	H$_2$SO$_4$ (25 wt.%)	–	W.I.
SSi30-wi	H$_2$SO$_4$ (30 wt.%)	–	W.I.
1SSi20-Cr-r-wi[a]	H$_2$SO$_4$ (20 wt.%)	K$_2$Cr$_2$O$_7$	W.I.
2SSi20-Cr-wi	H$_2$SO$_4$ (20 wt.%)	KCr(SO$_4$)$_2$	W.I.
SSi20-Cu-wi	H$_2$SO$_4$ (20 wt.%)	CuSO$_4$	W.I.
SSi20-Fe-wi	H$_2$SO$_4$ (20 wt.%)	FeCl$_3$	W.I.
SSi20-Zr-p	H$_2$SO$_4$ (20 wt.%)	ZrO$_2$	P.
SSi10-Zr-pwi	H$_2$SO$_4$ (10 wt.%)	ZrOCl$_2$	P.W.I.
SsiZr-sg	H$_2$SO$_4$ (96 wt.%)	Zr(i-OPr)$_4$	S.G.
SSi20-Zn-wi	H$_2$SO$_4$ (20 wt.%)	ZnCl$_2$	W.I.
SSi-Ti-sg	H$_2$SO$_4$ (96 wt.%)	Ti(i-OPr)$_4$	S.G.
SSi10-Ti-pwi	H$_2$SO$_4$ (10 wt.%)	TiCl$_4$	P.W.I.

[a] After impregnation of Cr(VI) on catalysts surface the metal was reduced with HCHO and washed with 1,2-dichloroethane in order to remove the excess of the reducing agents.

In the case of the sample prepared by the method called P.W.I. (precipitation wet impregnation) the catalyst was obtained by precipitation of the precursor with an aqueous solution of ammonia, then the precipitate was washed with plenty of water to remove the excess of base and finally impregnated with sulfuric acid by wet impregnation.

Samples of $H_2SO_4/ZrO_2/SiO_2$ and $H_2SO_4/TiO_2/SiO_2$ have been obtained by sol gel technique (S.G.): to a slurry of SiO_2 in an ethanol solution of zirconium or titanium isopropoxide an aqueous solution of sulfuric acid was added under stirring. The resulting slurries were stirred for 12 h, eliminated the surnatant solution by centrifugation and subsequently dried under N_2 flow at 383 K for 72 h.

A precipitation method (P.) has been employed to prepare SSi20-Zr. ZrO_2 was dissolved in H_2SO_4 at 96 wt.% and the resulting solution was added under vigorous stirring to a known amount of SiO_2. The slurry was then cooled at 273 K by an ice bath and an amount of H_2O sufficient to reach 20 wt.% of H_2SO_4 concentration was added. After 1 h the catalyst was centrifuged and desiccated at 383 K for 72 h under N_2 flow.

2.3. Catalysts characterization

The acid percentage composition in the solids after impregnation was determined by potentiometric titration against standard solutions of NaOH and checked before use. This method avoids the uncertainties due to hygroscopicity of the catalysts. Such a measure is actually the total exchange capability, rather than the measure of the H^+ title of the catalyst, since metal salt hydrolysis affects the measure on employing NaOH in catalyst titration.

The total ion exchange capacity in NaOH of a macroreticular sulfonated styrene divinyl benzene resins (Amberlyst 15^{TM}) is 4.7 meq $H^+/g_{catalyst}$, measured by back titration with standard solutions of HCl.

Surface area (BET), pore size distribution (BJH) and total pore volume (relative pressure of $p/p_0 = 0.98$) of the catalysts have been determined by N_2 adsorption and desorption at 94 K using an automatic adsorption unit (*Micromeritics* ASAP 2010C).

Cu, Cr, Fe and Zn content has been obtained by conventional spectrophotometric methods on solutions obtained by extraction of the metals from the catalysts. The composition of Ti and Zr promoted catalysts has been accounted from the theoretical value considering a complete hydrolysis of the precursors.

2.4. Synthesis of N-acetyl-caprolactam and acetyl-cyclohexanone oxime

The synthesis of the following compounds has been checked by NMR and GC–MS measurements. All the NMR spectra were recorded on a Bruker Avance 300 spectrometer. The ^{1}H spectra were recorded in CDCl$_3$ at room temperature, using TMS as internal reference. GC–MS measurements were carried out on a TRACE MS Finnigan ThermoQuest spectrometer.

N-Acetylcaprolactam was prepared by acetylation of ε-caprolactam with acetyl chloride in CH_2Cl_2 as a solvent. Reaction is practically quantitative in few minutes at 298 K. The crude product was distilled under reduced pressure and its purity checked by GC and HPLC analysis. Trifluoro-acetylcaprolactam was prepared following a similar procedure by using trifluoroacetic anhydride as trifluoroacetylating agent.

Acetylation of cyclohexanone oxime was carried out in CH_2Cl_2 as a solvent, in the presence of a stoichiometric amount of acetic anhydride. The reaction can be considered complete in 1 h at 298 K. The crude product was washed with a solution of Na_2CO_3 in an ice bath and then distilled under reduced pressure (b.p. 359–363 K, 400 Pa). The purity of the product was checked by GC and HPLC analysis.

2.5. Reaction procedure

The kinetic runs were performed in a well stirred glass reactor containing weighted samples of solvent, reagents and catalyst thermostated by circulation bath in the range 253–323 K. In order to avoid catalyst deactivation by air moisture all the operations were carried out into a glove box. Small amounts of the solution were drawn at different times and the samples were analyzed by GC (Agilent 6890) and GC–MS, (HP 5890–5231) using an HP5 capillary column (300 μm i.d. 30 m long, 95% methyl, 5% phenyl silicone phase); the samples were also checked by HPLC (Perkin Elmer 250 equipped with diode array detector) with a Lichrosphere 100 (RP-18, 5 m) column.

3. Results and discussion

3.1. $H_2SO_4/M/SiO_2$ catalysts characterization: H^+ title, metal content and surface area

The main features of the $H_2SO_4/M/SiO_2$ catalysts are reported in Table 2. As for H_2SO_4/SiO_2 [1] catalysts, the variation of surface areas and pore diameters of $H_2SO_4/M/SiO_2$ catalysts suggest that their synthesis involves only physical processes and that no reaction between promoters and support occurs. All the metal promoted catalysts have higher acid title than the corresponding neat H_2SO_4/SiO_2 catalyst, but this is a logical consequence of salts hydrolysis on employing NaOH in catalyst titration. The only exception is 1SSi20-Cr-r-wi catalyst, whose lower acid title can be ascribed to both the H_2SO_4 consumption during the

Table 2
$H_2SO_4/M/SiO_2$ catalysts characterization

Catalyst	Acids	Title H^+ (meq g^{-1})	Metal title (mmol g^{-1})	Surface area (m^2 g^{-1})	Pore volume (cm^3 g^{-1})	Average pore diameter (nm)
SSi10-wi	H_2SO_4 (10 wt.%)	3.0	–	290	0.79	8.6
SSi20-wi	H_2SO_4 (20 wt.%)	5.3	–	180	0.59	8.6
SSi25-wi	H_2SO_4 (25 wt.%)	6.3	–	145	0.45	8.4
1SSi20-Cr-r-wi	H_2SO_4 (20 wt.%)	3.5	0.41	139	0.47	8.5
2SSi20-Cr-wi	H_2SO_4 (20 wt.%)	5.8	0.40	185	0.58	8.8
SSi20-Cu-wi	H_2SO_4 (20 wt.%)	6.0	0.36	173	0.57	8.1
SSi20-Fe-wi	H_2SO_4 (20 wt.%)	6.1	0.28	179	0.61	8.3
SSi20-Zr-p	H_2SO_4 (20 wt.%)	5.5	0.21[a]	222	0.75	8.2
SSi10-Zr-pwi	H_2SO_4 (10 wt.%)	1	0.20[a]	105	0.55	8.3
SSiZr-sg	H_2SO_4 (96 wt.%)	0.9	0.2[a]	170	0.54	8.4
SSi20-Zn-wi	H_2SO_4 (20 wt.%)	5.8	0.32	80	0.56	8.5
SSi-Ti-sg	H_2SO_4 (96 wt.%)	0.8	0.2[a]	165	0.54	8.4
SSi10-Ti-pwi	H_2SO_4 (10 wt.%)	2.1	0.2[a]	100	0.51	8.2

[a] Obtained from the amount of precursor used in the preparation.

Cr(VI) reduction reaction and the higher number of washing steps.

Catalyst SSi20-Zr-p prepared by precipitation of $Zr(SO_4)_2$ by dilution of sulfuric acid from 96 wt.% to 20 wt.% shows both high surface area and acid content, suggesting the formation of a high surface area of Zr derivatives over the silica support.

Catalysts obtained by sol–gel technique have lower values of surface area if compared with those prepared with other methods and with higher sulfuric acid loading. The reason can be ascribed to a glass like surface formed over the silica surface.

3.2. Behavior of the catalysts towards cyclohexanone oxime rearrangement

The comparison of both activity and selectivity of the considered heterogeneous catalysts in the Beckmann rearrangement of cyclohexanone oxime was carried out taking into account the conversion values after 1 h of reaction (except for the poorly active Amberlyst 15). Table 3 reports the main results regarding activity and selectivity of the catalysts. The metal promoters strongly affect the results and a significant promoting effect can be observed in the cases of 2SSi20-Cr-wi and SSi20-Zr-p: these catalysts, if compared with neat H_2SO_4/SiO_2 systems of comparable H^+ title, show higher conversion and selectivity to ε-caprolactam. Moreover, despite the lower conversion compared with a corresponding title H_2SO_4/SiO_2 catalyst, 1SSi20-Cr-r-wi achieves a selectivity of 81% to ε-caprolactam. This evidence suggests a promotional effect of the Cr species on catalyst selectivity. Also Zr(IV) shows a similar behavior: catalysts with very low title of H^+ show a remarkable selectivity to ε-caprolactam (SSiZr-sg, SSi10-Zr-pwi). Unfortunately, the addition of metal-based promoters to supported sulfuric acid catalysts does not cause a decisive improvement of the performances in the Beckman rearrangement, since the fast catalyst deactivation is not significantly reduced and only Cr and Zr-based catalysts show a certain enhancement in catalyst selectivity. Titanium-promoted catalysts, instead, show only in one case of the two a promotional effect on selectivity, but always with very low activities. Cu and Zn-promoted catalysts are highly active, but also poorly selective to ε-caprolactam. Iron-based SSi20-Fe-wi catalyst represents the worst case, having both low activity and selectivity despite of an high exchange capacity.

The effect of the solvent on the performances of $H_2SO_4/M/SiO_2$ metal promoted catalysts has been investigated (see Supplementary data) and the results are in agreement with those obtained for H_2SO_4/SiO_2 catalysts reported in previous paper [1,27]. On increasing the dielectric constant of the solvent both the conversion and the selectivity towards ε-caprolactam rise. It is to be noted, moreover, that the increase of the polarity of the solvent decreases the lack in mass balance due to the oxime strongly adsorbed into the catalyst. 1,2-Dichloroethane represents a good compromise between activity and leaching of the acidic phase, which was observed using solvent with higher polarity such as nitromethane [1,27].

3.3. The Beckmann rearrangement of acetyl cyclohexanone oxime in the presence of solid acid catalysts

The acetylated oximes are activated with respect to Beckmann rearrangement because of the electro-withdrawing effect of the acetyl group which increases the electrophile nature of the oximes nitrogen [4,15–17]. The product of rearrangement of the acetyl cyclohexanone oxime is the N-acetyl-caprolactam, however, caprolactam and acetic acid are generally found because of the ease of the hydrolysis reaction [4,15–17]. Table 4 reports the results in the presence of different solid acid catalysts. Rearrangement of acetyl cyclohexanone oxime catalyzed by sulfonated resins is known for a long time and the comparison with different solid acid catalyst is reported in Table 4 [31]. Employing Amberlyst 15 conversion up to 43% is achieved and the rearrangement products are obtained in high yields. Also Nafion SAC 13, zeolites HY and Hβ catalyze the rearrangement of the acetyl cyclohexanone oxime, but the selectivity is lower than that of Amberlyst 15. Higher conversion is obtained in the presence of $H_2SO_4/M/SiO_2$ catalysts (SSi20 reaches 92% of conversion), but extensive formation of cyclohexanone and acetic acid are always observed. It is likely that both deacetylation and oxime hydrolysis could be related to the presence of hydroxyl group on the silica surface.

3.4. Influence of the solvent on the rearrangement of acetyl cyclohexanone oxime

Table 5 reports the results of the rearrangement of acetyl cyclohexanone oxime in different solvents employing Amberlyst 15 as an acid catalyst. After 20 h at 373 K the reactions do not reach the completeness, however in any case high selectivity in the rearrangement products is achieved. The best result has been observed

Table 3
Activity and selectivity of different silica supported solid acid catalysts in the Beckmann rearrangement of cyclohexanone oxime

Catalyst	Title H^+ (meq g^{-1})	Conversion (%)	TON	Caprolactam		Cyclohexanone	
				Selectivity (%)	Yield (%)	Selectivity (%)	Yield (%)
Amberlyst 15	4.6	0.5[a]	0.08	–	–	100	0.5
Amberlyst 15	4.6	6.9[a,b]	0.3	29	2	71	4.9
SSi10-wi	3.0	30	2.0	73	25	8.3	2.5
SSi20-wi	5.3	53	2.0	74	39	16	8.6
SSi25-wi	6.3	57	1.8	77	46	9	5
1SSi20-Cr-r-wi	3.5	22	1.3	81	18	7.2	1.5
2SSi20-Cr-wi	5.8	78	2.7	77	64	10	8
SSi20-Cu-wi	6.0	68	2.3	51	35	33	23
SSi20-Fe-wi	6.1	32	1.0	56	18	22	7
SSi20-Zr-p	5.5	61	2.2	80	49	6	3.5
SSi10-Zr-pwi	1	3	0.6	70	2.1	6	0.4
SSiZr-sg	0.9	2	0.4	75	1.5	10	0.2
SSi20-Zn-wi	5.8	69	2.4	49	34	32	22
SSi-Ti-sg	0.8	3	0.75	73	2.2	10	0.3
SSi10-Ti-pwi	2.1	8	0.76	51	4.1	25	2.0

Run conditions: oxime concentration 0.5 mol dm^{-3}, catalyst load 500 mg, reaction volume 20 ml, solvent: 1,2-dichloroethane, temperature 298 K, reaction time 1 h.

[a] Temperature of reaction 323 K.

[b] Time of reaction 20 h.

Table 4
Influence of the catalysts and reaction time on the Beckmann rearrangement of acetyl cyclohexanone oxime at 373 K in 1,2-dichloroethane

Catalyst	Time of reaction (h)	Conversion (%)	ACPL		CPL		CHE	
			Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)
Amberlyst 15	1	11	18	2	58	6.4	4.5	0.5
Amberlyst 15	20	43	28	12	56	24	4.7	2
HY	1	4	27	1.1	–	–	63	2.5
HY	20	20	30	6	–	–	55	11
Hβ	1	9	11	1	–	–	78	7
Hβ	20	58	7	4	16	9	71	41
Nafion SAC 13	1	18	33	6	22	4	39	7
Nafion SAC 13	20	25	16	4	16	4	56	14
SSi25	1	45	–	–	71	32	8.9	4
SSi25	20	92	1.1	1	57	52	27	25
1SSi20-Cr-r-wi	1	25	–	–	32	8	48	12
1SSi20-Cr-r-wi	20	44	–	–	25	11	52	23
SSi20-Fe-wi	1	14	–	–	57	8	21	3
SSi20-Fe-wi	20	75	–	–	19	14	35	26
SSi20-Zr-wi	1	40	–	–	40	16	53	21
SSi20-Zr-wi	20	81	–	–	26	21	44	36

ACPL: *N*-acetyl-caprolactam, CPL: ε-caprolactam, CHE: cyclohexanone. *Run conditions*: cyclohexanone oxime 0.21 mol d^{-3}, reaction volume: 6 ml, catalyst 0.12 g.

in toluene where 55% of conversion is obtained. High yields in ε-caprolactam were observed employing 1,2-dichloroethane or nitromethane as solvents. The amount of water in solution is not sufficient to justify the elevate hydrolysis of acetyl caprolactam, but the water adsorbed on the sulfonic group of the resin, even if desiccation of the catalyst has been carried out before each reaction, may explain such a behavior. It is well known, in fact, that the sulfonated resins have a great tendency to retain water molecules on the sulfonic groups and for this reason the presence of water cannot be excluded [28]. On the basis of the previous considerations it is likely that the differences in ε-caprolactam yield could be due to the influence of the solvent polarity on the acetyl caprolactam hydration rate, which is higher in polar solvents because of the stabilization by solvation of the charged transition state [29]. Furthermore, desorption of the high-polarity hydration products is enhanced in polar solvents [30]. Finally, the presence of acetic acid favors the de-acetylation process and, for instance, in the presence of an equimolar amounts of acetic acid and acetyl cyclohexanone oxime the conversion to acetyl caprolactam is practically suppressed.

After 20 h the conversion (58% in toluene) is practically stabilized and the reaction does not proceed further. Such a behavior can be ascribed to catalyst deactivation due to irreversible adsorption of by-products on the acid sites of the catalyst.

3.5. Reactivity of some potential organic promoters in the Beckmann rearrangement of cyclohexanone oxime

Table 6 reports the results of different organic compounds employed as promoters in the Beckmann rearrangement of cyclohexanone oxime. Acetic anhydride reacts almost quantitatively with acetyl cyclohexanone oxime but, under these conditions, no traces of rearrangement products have been found. Practically only a small amount of cyclohexanone, formed from cyclohexanone oxime hydrolysis, has been observed. Phthalic anhydride, which is sparingly soluble in 1,2-dichloroethane, does not react at room temperature and only in small extent (conversion 2%) at 373 K, however, ε-caprolactam is obtained suggesting that also phthalic anhydride has a promotional effect on cyclohexanone oxime rearrangement. Acetyl chloride readily reacts with cyclohexanone oxime at room temperature giving the corresponding acetyl oxime. Furthermore at 373 K the formation of rearrangement products is observed due to the catalytic action of HCl. Benzoyl chloride gives *N*-benzoylcaprolactam and ε-caprolactam together with a complex mixture of condensation products also at room temperature. No reaction between cyclohexanone oxime and ethyl formate, ethyl benzoate or methyl ortoformate occur at 373 K and only cyclohexanone oxime hydrolysis can be detected after 20 h of reaction. Trichlorotriazine gives ε-caprolactam in good yields both in 1,2-dichloroethane and nitromethane as solvents but a remarkable loss

Table 5
Influence of the solvent and of the reaction time on the Beckmann rearrangement of acetyl cyclohexanone oxime in the presence of Amberlyst 15 at 373 K

Solvent	Time of reaction (h)	Conversion (%)	ACPL		CPL		CHE	
			Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)
Toluene	1	18	37	6.7	39	7	5.5	1
Toluene	20	58	47	27	38	22	5.2	3
DCE	1	11	18	2	58	6.4	4.5	0.5
DCE	20	43	28	12	56	24	4.7	2
DCE[a]	1	17	8.8	1.5	47	8	35	6
DCE[a]	20	59	3.5	2.1	71	42	17	10
DCE[b]	1	7.2	98	7.0	–	–	–	–
DCE[b]	20	95	42	40	–	–	–	–
NM	1	9.1	2.2	0.2	78	7.1	7.7	0.7
NM	20	39	7.7	3	74	29	7.7	3

ACPL: *N*-acetyl-caprolactam, CPL: ε-caprolactam, CHE: cyclohexanone. *Run conditions*: cyclohexanone oxime 0.21 mol dm^{-3}, reaction volume 6 ml, Amberlyst 15 0.12 g.
[a] Reaction carried out in the presence of 0.21 mol dm^{-3} of CH$_3$COOH.
[b] Reaction carried out in the presence of 1.0 mol dm^{-3} of (CH$_3$CO)$_2$O.

Table 6
Activity and selectivity of some organic compounds in the Beckmann rearrangement of cyclohexanone oxime after 1 h of reaction

Organic catalyst	Solvent	Temp. (K)	Conv. (%)	Addition products		Rearrangement products		CPL		CHE	
				Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)
Ac_2O	TOL	373	100	98	98	–	–	–	–	0.2	0.2
Ac_2O	DCE	298	98	100	98	–	–	–	–	–	–
Ac_2O	DCE	373	100	96	96	–	–	–	–	1.2	1.2
Ac_2O	NM	373	100	96	96	–	–	–	–	1.5	1.5
Ac_2O	–	298	100	99	99	–	–	–	–	–	–
PA	DCE	298	–	–	–	–	–	–	–	–	–
PA	DCE	373	2	20	0.4	–	–	10	0.2	55	1.1
AcCl	DCE	298	100	–	98	–	–	–	–	–	–
AcCl	DCE	373	100	94	94	2.0	2.0	1	1	1.1	1.1
PhCOCl	DCE	298	100	1.8	1.8	39	39	1.3	1.3	2.9	2.9
PhCOCl	DCE	373	100	4	4	12	12	5	5	9	9
HCOOEt	DCE	373	–	–	–	–	–	–	–	–	–
PhCOOMe	DCE	373	–	–	–	–	–	–	–	–	–
MOF	–	373	–	–	–	–	–	–	–	–	–
TCT	DCE	298	83[a]	–	–	–	–	40	33	2.6	2.2
TCT	NM	298	80[a]	–	–	–	–	36	29	6.4	5.1

Conv.: conversion, select.: selectivity, CPL: ε-caprolactam, CHE: cyclohexanone, TOL: toluene, DCE: 1,2-dichloroethane, NM: nitromethane, PA: phthalic anhydride, MOF: methyl ortoformate, TCT: trichlorotriazine. *Run conditions*: cyclohexanone oxime 0.2 mol dm^{-3}, reaction volume 6 ml, cyclohexanone oxime/promoter ratio 1/5, except for TCT ratio 1/3.

[a] Formation of caprolactam dimer has been observed, together with other products of condensation.

in mass balance is observed by GC analysis. The addition of water at the end of the reaction does not give any variation in the yields of the products.

3.6. Influence of some organic cocatalysts on the Beckmann rearrangement of cyclohexanone oxime in the presence of macro-reticular sulfonated styrene divinyl benzene resins (Amberlyst 15^{TM})

As seen in Table 3, Amberlyst 15 practically does not catalyze Beckmann rearrangement of cyclohexanone oxime [1], but it works for acetyl cyclohexanone oxime (see Table 4) [31]. For this reason, the addition of the solid acid into the systems described in the previous chapter allows to test the effective promotional effect of each compound. Moreover, the polymeric nature of the sulfonated resin avoids the leaching of the acid phase which is observed in the presence of $H_2SO_4/M/SiO_2$ catalysts with high polar compounds. On comparing Table 7, which reports the results of these experiments, with Table 6 it can be clearly observed that the presence of the solid acid catalyst led to an increase in the rearrangement products. It is to be noted that the cyclohexanone oxime derivatives are less basic than the original oxime because of the presence of electron-withdrawing substituents, thus many products of derivatization (in the case of acetic anhydride, for example, acetic acid) are not able to efficiently protonate the species formed, such a reaction that can be instead easily performed by Amberlyst 15. The nature of the derivatization reagents used strongly affects, however, the rearrangement. The acetyl chlorides-Amberlyst 15 system, compared to acetic anhydride-Amberlyst 15, shows a comparable yield in the rearrangement products but with a higher yield in cyclohexanone probably due to the presence of HCl in the reaction mixture. Benzoyl chloride shows complex mixtures of products and the yield in caprolactam and its derivatives is poor. The reaction of cyclohexanone oxime with methyl ortoformate does not occur and therefore no rearrangement happens. TCT-Amberlyst 15 system led to a total conversion of cyclohexanone oxime, but the yield of ε-caprolactam was lower than that obtained without acid catalyst, suggesting a quite complex reaction path.

3.7. N-Acetyl-caprolactam—Amberlyst 15 as catalytic system for the Beckmann rearrangement of cyclohexanone oxime

An attempt to combine the effects acid catalysts and organic promoters in a catalytic cycle consists on using the acetylation properties of acetyl caprolactam to obtain acetyl cyclohexanone oxime from cyclohexanone oxime and ε-caprolactam [32], as depicted in the catalytic cycle reported in Scheme 2. Amberlyst 15 is used instead of $H_2SO_4/M/SiO_2$ catalysts because it allows to avoid the problems related to the acid phase leaching in strongly polar solvents.

Cyclohexanone oxime should compete with water on reacting with acetyl caprolactam, thus reducing the hydrolysis of this compound and increasing the catalytic life of the sulfonated resin.
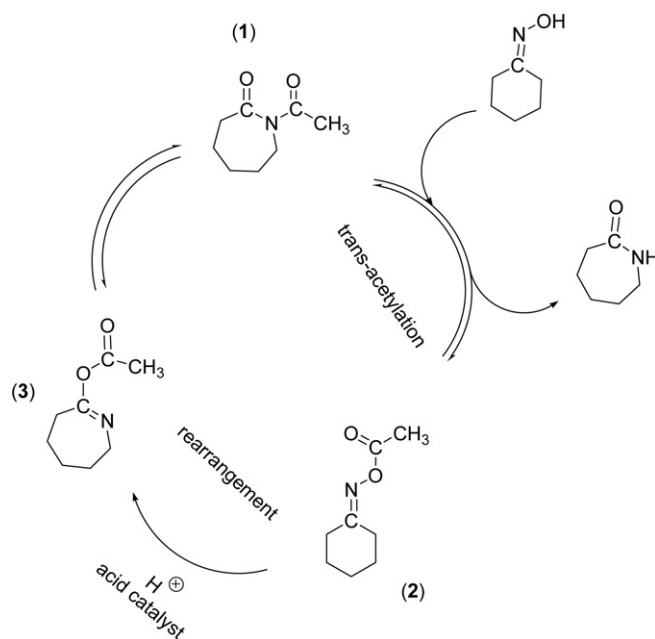
Scheme 2. Catalytic cycle of *N*-acetyl-caprolactam as co-catalyst.

Table 7
Activity and selectivity of Amberlyst 15 in the Beckmann rearrangement of cyclohexanone oxime in 1,2-dichloroethane in the presence of organic co-catalysts

Organic co catalyst	Time of reaction (h)	T (K)	Conv. (%)	Addition products		Rearrangement products		CPL		CHE	
				Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)
Ac$_2$O	1	373	98	61	60	18	17	9.3	9.2	2.2	2.2
Ac$_2$O	20	373	99	41	40	42	41	10	10	0.3	0.3
AcCl	1	298	99	82	82	1.0	1.0	3.0	3.0	6.7	6.6
AcCl	1	373	99	59	58	21	21	10	10	7.0	6.9
AcCl	20	373	99	14	14	1.0	1.0	30	30	7.5	7.4
PhCOCl	1	298	99	30	30	16	16	2.0	2.0	11	11
PhCOCl	20	373	99	4.6	4.5	15	15	3.0	3.0	8.9	8.8
HCOOEt	20	353	1.1	–	–	–	–	–	–	100	1.1
HCOOEt	20	373	1.2	–	–	–	–	–	–	100	1.2
PhCOOMe	20	353	1.0	–	–	–	–	–	–	100	1.0
PhCOOMe	20	373	1.1	–	–	–	–	–	–	100	1.1
MOF	20	353	0.9	–	–	–	–	–	–	100	0.9
MOF	20	373	1.0	–	–	–	–	–	–	10	1.0
TCT	20	298	89[a]	–	–	–	–	38	34	1.2	1.1
TCT	20	353	98[a]	–	–	–	–	33	33	1.1	1.1

Conv.: conversion, select.: selectivity, CPL: ε-caprolactam, CHE: cyclohexanone, MOF: methyl ortoformate, TCT: trichlorotriazine. *Run conditions*: cyclohexanone oxime 0.2 mol dm^{-3}, reaction volume 6 ml, Amberlyst 15 0.1 g, cyclohexanone oxime/promoter ratio = 1/5, except for TCT ratio = 1/3.

[a] Formation of caprolactam dimer has been observed, together with other products of condensation.

Table 8
Influence of the solvent on the Beckmann rearrangement of cyclohexanone oxime promoted by *N*-acetyl-caprolactam in the presence of Amberlyst 15 after 20 h of reaction

Solvent	$\frac{AcCPL}{COX}$ (molar ratio)	T (K)	Conversion (%)	ACPL decrease (%)	yield[a] (%)		
					ACOX	CPL	CHE
DCE	1	373	95	55	39	45	12
DCE	5.6	373	100	7	30	60	4
DCE	8.3	373	100[b]	2	45	51	3.9
DCE	5.9	298	53	5	25	25	3
Benzene	5.9	373	100	18	42	54	8
Toluene	5.9	373	100	8	18	70	7
Chloroform	4.9	373	100	25	20	70	5
NM	6.3	373	100	40	8	80	7

COX: cyclohexanone oxime, ACPL: *N*-acetyl-caprolactam, ACOX: acetyl cyclohexanone oxime, CPL: ε-caprolactam, CHE: cyclohexanone, NM: nitromethane. *Run conditions*: cyclohexanone oxime 0.18 mol dm^{-3}, reaction volume 10 ml, Amberlyst 15 0.12 g.

[a] Yield calculated from the amount of cyclohexanone oxime.
[b] No acid catalysts.

Table 8 reports the results of the Beckmann rearrangement of cyclohexanone oxime promoted by *N*-acetyl-caprolactam. "*N*-Acetyl-caprolactam decrease" was chosen as the parameter to evaluate the life of the catalytic system, since the constancy of *N*-acetyl-caprolactam concentration in the reaction environment is a neces-sary condition for the maintenance of the catalytic cycle reported in Scheme 2.

Figs. 1 and 2 report the concentration profiles of the described reaction in 1,2-dichloroethane and in toluene. In both cases cyclohexanone oxime readily reacts with acetyl caprolactam,
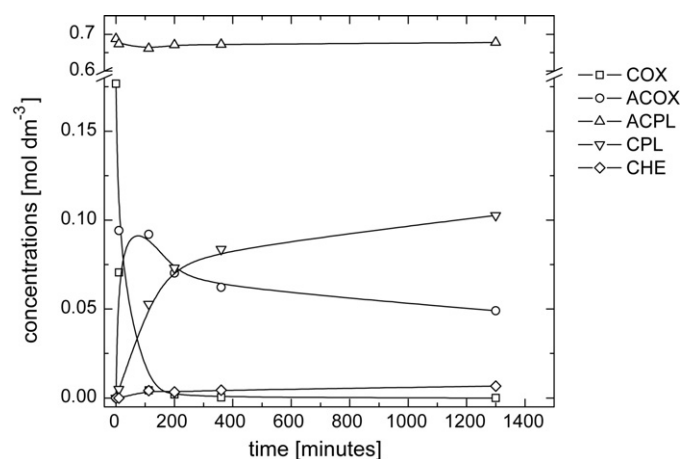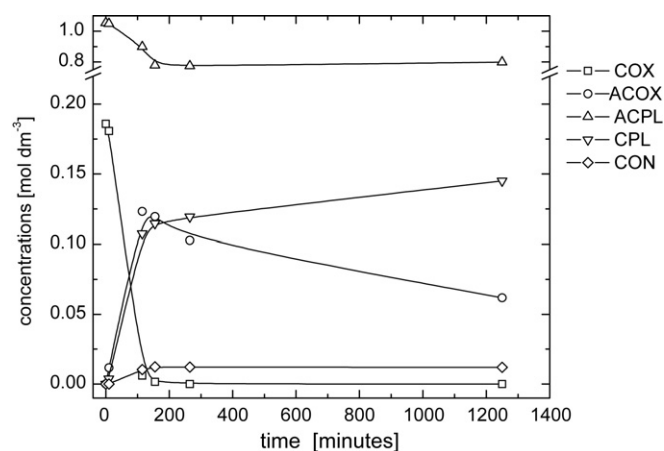

Fig. 1. Concentration profiles in the Beckmann rearrangement of cyclohexanone oxime catalyzed by Amberlyst 15 and promoted by acetyl caprolactam in 1,2-dichloroethane as a solvent. *Run conditions*: cyclohexanone oxime 0.18 mol dm^{-3}, reaction volume 10 ml, Amberlyst 15 0.12 g.

Fig. 2. Concentration profiles in the Beckmann rearrangement of cyclohexanone oxime catalyzed by Amberlyst 15 and promoted by acetyl caprolactam in toluene as a solvent. *Run conditions*: cyclohexanone oxime 0.18 mol dm^{-3}, reaction volume 10 ml, Amberlyst 15 0.12 g.

Table 9
Influence of trifluoroacetic anhydride and trifluoroacetic acid in the Beckmann rearrangement of cyclohexanone oxime and acetyl cyclohexanone oxime in 1,2-dichloroethane as a solvent

Organic co catalyst	Time of reaction (h)	T (K)	Conv. (%)	Addition products		Rearrangement products		CPL		CHE	
				Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)	Select. (%)	Yield (%)
$(CF_3CO)_2O$[a]	1	298	100	42	42	2	2	55	55	1	1
$(CF_3CO)_2O$[a]	20	298	100	3.7	3.7	3.5	3.5	90	90	1	1
$(CF_3CO)_2O$	1	298	100	70	70	8	8	18	18	–	–
$(CF_3CO)_2O$	20	298	100	50	50		–	45	45	–	–
$(CF_3CO)_2O$	1	373	100	0.4	0.4	0.5	0.5	98	98	0.2	0.2
CF_3COOH	1	298	–	–	–	–	–	–	–	–	–
CF_3COOH	20	298	–	–	–	–	–	–	–	–	–
CF_3COOH	1	373	16	–	–	6.3	1	75	12	13	2.1
CF_3COOH	2	373	30	–	–	3.3	1	80	24	11	3.3
CF_3COOH	20	373	100	–	–	5	5	90	90	3.5	3.5
CF_3COOH[b]	2	298	5.2	–	–	–	–	–	–	94	4.9
CF_3COOH[b]	1	373	100	–	–	1.8	1.8	30	30	12	12
$(CF_3CO)_2O$[c]	1	373	100	–	–	1.0	1.0	97	97	1.1	1.0
$(CF_3CO)_2O$[c]	20	373	100	–	–	–	–	97	97	2.0	2.0
$CF_3CO\text{-}CPL$[c]	1	353	90	8.1	7.3	0.6	0.5	91	82	1.6	1.4
$CF_3CO\text{-}CPL$[c]	90	353	97	–	–	–	–	90	88	10	9

Conv.: conversion, select.: selectivity, CPL: ε-caprolactam, CHE: cyclohexanone. *Run conditions*: cyclohexanone oxime 0.20 mol dm^{-3}, reaction volume 6 ml, CF$_3$COOH 0.2 g, cyclohexanone oxime/promoter 1/5.

[a] No solvent.
[b] Acetyl cyclohexanone oxime as substrate.
[c] 0.1 g of Amberlyst 15 as solid acid catalyst.

but the formation of ε-caprolactam and the rearrangement of acetyl cyclohexanone oxime are neither fast nor quantitative processes. Furthermore, the rearrangement is as slow as the one observed for acetyl caprolactam and hydrolysis of acetyl caprolactam occurs in practically the same extent. The differences between 1,2-dichloroethane and toluene are likely due to the different adsorption equilibria between the solid catalyst and the compounds in solution, but the final conversions are practically the same in both the solvents.

3.8. Preliminary results regarding the homogeneous Beckmann rearrangement of cyclohexanone oxime catalyzed by trifluoroacetic acid and trifluoroacetic anhydride

The last part of our current studies was focused on the influence of electro-withdrawing substituents stronger than the acetyl group. In particular, the trifluoroacetyl CF$_3$-CO group was considered using
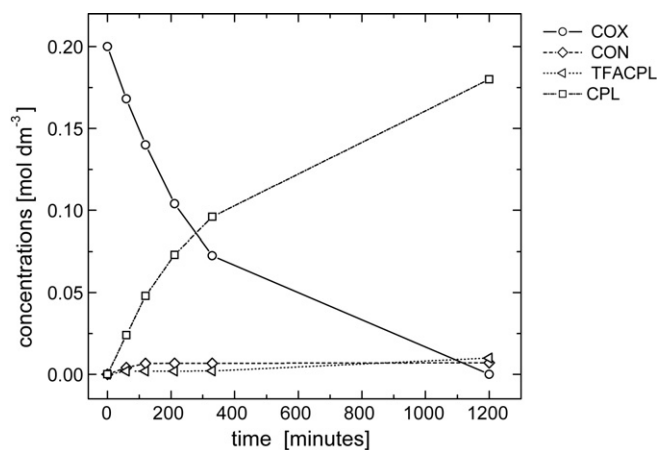

Fig. 3. Concentration profile of the Beckmann rearrangement of cyclohexanone oxime catalyzed by trifluoroacetic acid in 1,2-dichloroethane as solvent. *Run conditions*: cyclohexanone oxime = 0.20 mol dm^{-3}, reaction volume 6 ml, CF$_3$COOH 0.2 g, 373 K.

trifluoroacetic anhydride as derivatizing agent and trifluoroacetic acid as Brønsted acid. Table 9 reports the influence of trifluoroacetic anhydride and trifluoroacetic acid in the Beckmann rearrangement of cyclohexanone oxime and acetyl cyclohexanone oxime in 1,2-dichloroethane. The conversion of cyclohexanone oxime is quantitative and the yield in rearrangement products is in many cases quantitative. Of particular interest results the high yield in ε-caprolactam without acid catalyst also at 298 K using trifluoroacetic anhydride, suggesting a strong activation effect of the trifluoroacetyl group. Even more interesting is the ability of trifluoroacetic acid to catalyze the rearrangement of cyclohexanone oxime, with a quantitative conversion of the starting oxime and a high yield of the amide. Fig. 3 reports the concentration profile of the Beckmann rearrangement of cyclohexanone oxime catalyzed by trifluoroacetic acid in 1,2-dichloroethane as solvent. On the contrary, acetyl cyclohexanone oxime in the presence of trifluoroacetic acid gives a complex mixture of rearrangement and condensation products that are not useful for synthetic application. The use of trifluoroacetyl caprolactam as promoter in the presence of Amberlyst 15 as acid catalyst in a catalytic cycle similar to the one of Scheme 2 gives poor results, since trifluoroacetyl caprolactam is a highly reactive species that almost immediately hydrolyzes to caprolactam.

4. Conclusions

In this paper the influence of some metal-based promoters on the selectivity of supported sulfuric acid in the Beckmann rearrangement of cyclohexanone oxime was studied together with the role of several organic promoters with and without acid catalyst. The main results of this research are:

(1) there is a specificity of each metal on catalyst selectivity;
(2) acetic anhydride and trifluoroacetic anhydride as promoters give the best results;
(3) acetyl cyclohexanone oxime rearranges to acetyl caprolactam in the presence of Amberlyst 15 at 373 K, but cyclohexanone and caprolactam are observed in any case, suggesting that the hydrolysis reaction is not suppressed;

(4) cyclohexanone oxime in 1,2-dichloroethane in the presence of CF₃COOH as acid catalyst gives a quantitative conversion and a high yield in ε-caprolactam.

These results are the starting point for future investigation employing the synergic effect of organic promoters and heterogeneous catalysts. The features of the homogeneous system 1,2-dichloroethane/CF₃COOH require further studies to understand the specific action of such an acid in the Beckmann rearrangement of cyclohexanone oxime.

Acknowledgement

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2008.05.007.

References

[1] N.C. Marziano, L. Ronchin, C. Tortato, C. Badetti, A. Vavasori, J. Mol. Catal. A Chem. 277 (2007) 221.
[2] M.I. Vinnik, N.G. Zarakhani, Russian Chem. Rev. 36 (1967) 51.
[3] H. Stephen, B. Staskum, J. Chem. Soc. (1956) 980.
[4] B. Jones, Chem. Rev. 35 (1944) 335.
[5] S. His, C. Meyer, J. Cossy, G. Emeric, A. Greinerb, Tetrahedron Lett. 44 (2003) 8581.
[6] C.J. Milios, T.C. Stamatatos, S.P. Perlepes, Polyhedron 25 (2006) 134.
[7] V. Yu Kukushkin, A.J.L. Pombeiro, Coord. Chem. Rev. 156 (1996) 333.
[8] P. Chaudhuri, Coord. Chem. Rev. 243 (2003) 143.
[9] V. Yu Kukushkin, A.J.L. Pombeiro, Coord. Chem. Rev. 181 (1999) 147.
[10] L. Tschugaeff, Chem. Ber. 23 (1890) 1.
[11] K. Narasaka, H. Kusama, Y. Yamashita, H. Sato, Chem. Lett. (1993) 489.
[12] H. Kusama, Y. Yamashita, K. Narasaka, Bull. Chem. Soc. Jpn. 68 (1995) 373.
[13] M. Arisawa, M. Yamaguchi, Org. Lett. 3 (2001) 311.
[14] E. Beckmann, Chem. Ber. 19 (1886) 988.
[15] A.H. Blatt, Chem. Rev. 12 (1933) 215.
[16] A.W. Chapmann, C.C. Howis, J. Chem. Soc. (1933) 806.
[17] B.B. Lampert, F.G. Bordwell, J. Am. Chem. Soc. 73 (1951) 2369.
[18] J.D. McCullough Jr., D.Y. Curtin, I.C. Paul, J. Am. Chem. Soc. 94 (1972) 874.
[19] L. De Luca, G. Giacomelli, A. Porcheddu, J. Org. Chem. 67 (2002) 6272.
[20] Y. Furuya, K. Ishihara, H. Yamamoto, J. Am. Chem. Soc. 127 (2005) 11240.
[21] R.F. Brown, O. van Gulick, G. Schmid, J. Am. Chem. Soc. 77 (1955) 1094.
[22] R. Huisgen, J. White, H. Walz, W. Jira, Annalen 604 (1957) 191.
[23] N.C. Marziano, C. Tortato, L. Ronchin, O. Tonon, R. Bertani, Int. J. Chem. Kin. 36 (2004) 417.
[24] B.J. Gregory, R.B. Moodie, K. Schofield, J. Chem. Soc. (B) (1970) 338.
[25] A.C. Huitric, S.D. Nelson, J. Org. Chem. 34 (1969) 1232.
[26] B. Bjoerkqvist, H. Toivonen, J. Chromatogr. 178 (1979) 271.
[27] Unpublished results, available on supplementary data.
[28] G. Zundel, Adv. Chem. Phys. 111 (2000) 1.
[29] C. Reichardt, Solvents and Solvent Effects in Organic Chemistry, second ed., VCH, Weinheim, 1988, p. 79.
[30] C. Ngamcharussrivichai, P. Wu, T. Tatsumi, J. Catal. 227 (2004) 448.
[31] G. Jennings, United Kingdom Patent 1,029,201 to Inventa A.G. (1966).
[32] I. Fuijta, I. Toru, Y. Toyonaka, S. Deguchi, United States Patent 3,757,007 to Kabushiki Kaisha (1973).