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ABSTRACT

NEW HETEROGENEOUS CATALYSTS FOR C-N AND C-C BOND FORMATION

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Introduction

The thesis treats a domain of continuous interests on international area, that is the study of different heterogeneous catalytic processes that leads to the formation of carbon-carbon respectively, carbon-nitrogen bonds. The thesis treats this subject in two different perspectives, the first one is the obtaining and characterisation of new chemical species with catalytic activity, and the second one the study of the respective catalytic processes. There were taken into consideration three series of catalysts: *(i)* zeolites, tested in the hydroamination reaction, (*ii*) the catalysts obtained through the precipitation-deposition of gold and copper on TiO_2, catalysts tested in the amination reaction of bromobenzene with aniline, and (*iii*) a series of bis(oxazoline) metal(II) complexes supported on silica and carbon supports by non-covalent immobilisation using an ionic liquid tested in Diels-Alder and Aldol-Mukaiyama reaction.

The objectives of the thesis

The goal of this thesis was to investigate new heterogeneous catalysts for hidroamination reaction, C-N coupling reaction and Diels-Alder and Aldol-Mukaiyama reaction. For the hydroamination reaction there were tested comercial zeolites with different structures and chemical compositions purchased from different companies (large pore mordenite, mordenite CBV 20A and mordenite CBV 30A were purchased from Zeolyst International, while three H-beta zeolites H-BEA 25, 30 and 75, respectively, were received from PQ-Valfor Company). The commercial zeolites have been characterized as well using nitrogen adsorption–desorption isotherms, NH3-TPD, Py-FT-IR etc.

The hydroamination reaction between aniline and styrene was investigated in the presence of these catalysts. There was studied also the influence of aniline basicity in the hydroamination reaction. For this purpose there were used anilines with different substituents to the aromatic ring this leading to different basicities. Adding a Lewis acid cocatalyst, $Sc(OTf)_3$, to the beta 25 and beta 30 zeolites leads to a decrease of the conversion. But the selectivities presented good yields in Markovnikov product. In the same time using pure $Sc(OTf)_3$ the conversion was superior to the BEA-25/$Sc(OTf)_3$ sau BEA-30/$Sc(OTf)_3$ mixtures, but still inferior to the simple zeolites.

For the C-N coupling reaction there were chosen metals from the Ib group: gold and copper. The proposed catalysts are important because they can be recicled. The obtained catalysts were characterized using different techniques: nitrogen adsorption at the temperature of liquid nitrogen, DR-UV-Vis, DRIFT, RAMAN, XRD, XPS, TEM, HRTEM. That was studied the amination reaction of bromobenzene with aniline in diferent solvents. This reaction requires strong basic conditions that are furnished adding to the reaction media an alcoxide, carbonate or an alkaline hydroxide. In the study presented in this thesis there were used different anorganic bases like NaOH, KOH, Na_2CO_3, CsF or potassium ethoxide.

A series of bis(oxazoline) metal(II) complexes has been supported on silica and carbon supports by non-covalent immobilisation using an ionic liquid. The catalytic performance of these solids was compared for the enantioselective Diels–Alder reaction between N-acryloyloxazolidinone and cyclopentadiene and the Mukaiyama-aldol reaction between methyl pyruvate and 1-methoxy-1-trimethylsilyloxypropene. In both reactions the enantioselectivity was strongly influenced by the choice of support displaying enantioselectivies (ee values) up to 40% higher than those conducted under homogeneous reaction conditions.

The structure of the thesis

The thesis is structured on 5 chapters. The **1st** and **2nd chapter** of this thesis presents a critical analysis of the literature. A special attention was concentrated on the relation reaction-catalysts. The analysis was concentrated also on the catalyst purpose, solvent, ligands, base, substrate and reaction parameters.

The chapter 3 of this thesis treats the direct amination of bromobenzene with aniline carried out on heterogeneous Au-TiO_2 and Cu-TiO_2 catalysts prepared using the deposition-precipitation method [1].

The catalysts were prepared by precipitation deposition which consisted in the addition of the support TiO_2 Degussa P25 over 100 cm^3 aqueous solution of $HAuCl_4 \times 3 H_2O$/ $Cu(NO_3)_2$ (0.2 M). The pH of the solution was stabilized at pH = 8-9 by dropwise adding a NaOH (0.2 M) solution, then the support was added and the mixture was stired at 80°C for 12 hours. The suspension was filtered, washed with distilled water until no Cl^- was observed and then was dried in vacuum at 80^{o}C for 48 hours. In this way there were obtained samples with 0.3, 0.5, 0.7, 0.9, 1% Au and respectively 1 and 2% Cu/TiO_2.

The catalytic tests were done in a stainless steel autoclave loaded with:

a) for the case **Au/TiO_2** : 50 mg of catalyst, 93 mg aniline and 188 mg bromobenzene (molar ratio of 1:1.2), under atmospheric pressure and temperatures of 150-220 °C. Two kinds of solvents were used: i) basic solvents such as dimethyl carbonate (DMC), diphenyl carbonate (DPC), dimethylformamide (DMF) and pyridine; ii) non-polar aprotic solvents such as 1,4-dioxane and toluene. In the case of toluene 0.3 - 2 mmols potassium ethoxide was also added.
b) for the case **Cu/TiO_2**: 100 mg of catalyst, 93 mg aniline and 188 mg bromobenzene (molar ratio of 1:1.2), under atmospheric pressure and temperatures of 200 °C. 1,4-dioxane was used as a solvent and the base quantity was varied between 0.8-1.2 mmols.
c) for the case **catalyst free**: 1 mmol of amine and 188 mg bromobenzene (molar ratio of 1:1.2), under atmospheric pressure and temperatures of 200 °C. There were used 5 mL of solvent and 1.2 mmols potassium ethoxide.

Reactants and products were analyzed by CG-MS using a Trace GC 2000 coupled with DSQ MS from Thermo Electron Corporation. The structure of the resulted products was confirmed by ^{1}H- and ^{13}C-NMR spectroscopy using a Bruker AV 400 spectrometer, in DMSO solvent and Me_4Si as internal standard.

Literature provided clear evidences on pH importance in Buchwald-Hartwig amination. Strong basic conditions are necessarily and they are generally ensured by adding to the reaction system an alkaline hydroxide, carbonate or alcoxide [2]. However, the use of the basic reagents is strongly correlated to the nature of the solvent (ie to the solubility conditions) and in order to check the effect of these factors the amination of bromobenzene with aniline has been carried out in different solvents.

The **Au/TiO_2** catalysts were characterized using different techniques. Textural characteristics (surface are and pore diameter) were determined from the adsorption-desorption isotherms of nitrogen at -196 ^{o}C using a Micromeritics ASAP 2020 Surface Area and Porosity

Analyzer. DR-UV-Vis spectra exhibits absorption bands typical for the transitions between valence band and conduction band of commercial TiO_2 (P25) and due to the vibrations of superficial plasmons. It was suggested that the resonance of the superficial plasmons caused by the collective oscillations of the electrons from the surface of gold nanoparticles is the key factor of the promoting effect of gold on the TiO_2 activity [3]. RAMAN experiments confirmed the existence of interaction between gold and support, interaction that can be responsible for the existence of plasmons. The presence of metallic gold was confirmed by the XPS studies that indicated for the fresh samples the existence of titania only as Ti^{4+} species. TEM analysis indicated the fact that gold was deposited with a narrow distribution of particles and the density of the gold particles grows with the gold quantity. Au/Ti XPS ratio correlates very well with TEM analysis. Small gold quantities corresponds to small XPS Au/Ti ratios. In addition, XPS analysis for the investigated catalysts revealed the existence of potassium and bromine on the surface of the catalysts fact that was attributed to a strong interaction of the alkaline species with the oxygen anions from the surface [4].

The experimental data proved that indeed, 1.1 mmol of potassium ethoxide correlates very well with the aniline/bromobenzene molar ratio of 1/1.2, and represents the optimal composition to achieve high selectivities. Thus, irrespective of the solvent, both the aniline conversion and diphenylamine selectivity reached the highest values. However, it is important to notice again that the level of both conversion and selectivity is strongly influenced by the loading of gold loaded onto titania.

Working in DMC as a solvent leaded to a maximum in conversion (78%) and selectivity (37%) achieved on 0.9wt% Au/TiO_2. Further increase of the gold loading to 1.0% led to the same level of selectivity in diphenylamine and conversion of aniline. Although aniline conversion is relatively high, its reaction with DMC led to large amounts of by-products.

Using DPC led to a partial de decomposition of the solvent to phenol, while in DMF or pyridine as reaction solvents and Au/TiO_2 as catalysts neither aniline nor bromobenzene were converted indicating that such compounds are less reactive than DMC. Furthermore, the addition of an inorganic base as NaOH, KOH, Na_2CO_3, or CsF to the reaction medium had no effect on the catalytic performances.

The limitation in selectivity using DMC determined a change of strategy. The classic solvents employed in the Buchwald-Hartwig amination are either non-polar or aprotic in nature, such as *m*-xylene or dioxane [5]. Based on this state of the art we decided to investigate the Au/TiO_2 catalysts using similar solvents (e.g., 1,4-dioxane and toluene) and in the presence of potassium ethoxide, as a base.

Using toluene as a solvent there was observed: (i) the conversions and selectivities were smaller than the ones obtained in DMC, (ii) diphenylamine was the major product independently on the reaction conditions, (iii) the nature of by-products was different as a function of the amount of gold, suggesting the reaction is structural sensitive. The formation of the by-products is due to of an unproductive side reaction (involving molecules of toluene from the reaction medium) which can compete with reductive elimination wherein the amide undergoes beta hydride elimination to yield the hydrodehalogenated arene and most probably due to the toluene oxidation to benzaldehyde in the presence of the catalyst (that can liberate small amounts of network oxygen).

Working in dioxane leaded to a completely different behavior. Selectivity was improved. The best results were obtained for the catalyst with 0.7% Au, for which at conversions smaller than 20% only the desired product was formed. For conversions bigger than 30% there were formed also secondary products which leaded to a decrease of the selectivity in diphenylamine. Due to the Lewis basicity of the oxygen atoms, dioxane is capable to soluble many anorganic compounds. This property together with the basic character explain very well the results obtained in this solvent comparable with toluene.

Relying on the catalyst characterization and catalyst performances it can be said that the bromobenzene amination to diphenylamine is influenced by the particles dimension and their density. Thus, increasing the gold quantity the conversion and selectivity increases till 0.7%Au. A bigger quantity of gold leads to bigger gold particles and a weaker interaction with the support. Working with these heterogeneous catalysts you have the advantage that the KBr remains chemisorbed on the solid surface and it can be removed by simply washing with dioxane. Than the catalyst is simply recycled, four times, obtaining similar catalytic performances.

For the case **Cu/TiO$_2$**, the DR-UV-Vis spectra presents the absorption bands for the transitions between valence band and conduction band of commercial TiO$_2$. Comparable with the initial TiO$_2$, for the investigated samples there were observed absorption bands specific for Cu(I) and Cu(II). In accordance with spectroscopic evidences, XRD studies indicated that the crystalline structure of TiO$_2$ was maintained for all the samples. As a consequence the preparation procedure and heat treatment did not perturbed the crystalline structure of TiO$_2$.

In order to establish the optimal conditions to obtain high conversions and selectivities the influence of base quantity was studied. A linear increase in potassium ethoxide content from 0.8 to 1.2 mmol resulted in a linear increase in conversion of aniline till 44% with a maximum in selectivity in diphenylamine of 94% for 0.5 mmols of base. Catalytic tests showed that conversion was correlated with potassium ethoxide content from the reaction medium. Optimizing the reaction by changing the amount of catalyst did not lead to a significant increase of selectivity in diphenylamine. Therefore optimal conditions to achieve high conversions and selectivities are as follows: 1.2 mmols potassium ethoxide molar ratio aniline / bromobenzene 1/1.2 and 100 mg catalyst Cu/TiO$_2$.

Catalyst containing 1% Cu (I) (prepared by treating the sample containing Cu (II) at 300^{0}C in nitrogen flow) was more active than that containing 1% Cu (II). Thus for Cu (I) the conversion was 44% while for Cu (II) the conversion was only 17%. No major differences were observed in terms of selectivity: for Cu (I) diphenylamine selectivity was 91% while for Cu (II) of 95%.

Catalysts Cu (I)/TiO$_2$ with various amounts of copper (1% and 2% wt) deposited on the support prepared by reduction of glucose at 80^{0}C during the precipitation-deposition were tested under the same conditions, leading to a significant decrease in conversion (from 31% to 22%), while the selectivity was slightly improved (from 91% to 94%). These results may suggest that the residues generated by thermal decomposition of carbonaceous sugars during catalyst preparation would block the catalytic centers.

A comparison between the activities of catalysts pretreated in different conditions, showed that those who were treated in nitrogen flow at 300^{0}C, showed higher activity than those reduced with glucose.

X% Cu/TiO_2 catalysts proved to be active in direct reaction of bromobenzene. The deposition of copper on titanium dioxide occurred with copper particles formation with controlled oxidation state and size. Interaction of these particles with the support stabilized the metallic state of copper as Cu (I). The amination of bromobenzene with aniline on these catalysts is dependent on both the amount of copper-induced properties and the reaction medium. As reported in the literature the presence of a base is required in this reaction.

In the case of catalytic tests performed in the absence of catalyst was studied the direct amination of bromobenzene with various compounds containing NH bonds (aniline, 2.6-dimethylaniline, 4-isopropilaniline, 4-ethylaniline, 4-chloroaniline, morpholine, 1-methyl-piperazine, benzylamine) only in the base presence.

The best results were obtained with aniline (64% selectivity for conversion of 70.8%). When aniline replaced with methyl in 2.6 positions was used there were achieved more modest results (26.6% conversion, 82.6% selectivity) than when were used the para-substituted aniline with chlorine (40% conversion, 46.9% selectivity), isopropyl (34.8% conversion, 87.8% selectivity), ethyl (41.7% conversion, 89.7% selectivity). A cyclic amine with low basicity, morpholine, was more reactive than para-substituted aromatic amines (conversion 46% for a selectivity of 90%), results comparable to those of 1-methylpiperazine case (39.3% conversion, 93.5% selectivity).

Chapter 4 presents the results for **the hydroamination reaction.** There were tested heterogeneous zeolites like Beta 25, 30, 75 and mordenites in the reaction between aniline and styrene. There was studied also the influence of aniline basicity in the hydroamination reaction. For this purpose there were used zeolites as catalysts because they can be recycled. Therefore commercial zeolites with different structures and chemical compositions purchased from different companies (large pore mordenite, mordenite CBV 20A and mordenite CBV 30A were purchased from Zeolyst International, while three H-beta zeolites H-BEA 25, 30 and 75, respectively, were received from PQ-Valfor Company).

The zeolites have been characterized using nitrogen adsorption–desorption isotherms, NH_3-TPD, Py-FT-IR etc. The catalytic tests were realized in a stainless steel autoclave loaded with 50 mg of catalyst, 93 mg of aniline/138 mg p-NO_2-aniline/109 mg 3-OH-aniline/128 mg p-Cl-aniline and 208 mg of styrene (molar ratio 1:2), at atmospheric pressure and temperature ranging between 90-150^{0}C. Toluene was used as a nonpolar, aprotic solvent. Reactants and products were analyzed by CG-MS using a Trace GC 2000 coupled with DSQ MS from Thermo Electron Corporation. The structure of the resulted products was confirmed by ^{1}H- and ^{13}C-NMR spectroscopy using a Bruker AV 400 spectrometer, in DMSO solvent and Me_4Si as internal standard.

The hydroamination reaction between aniline and styrene was investigated in the presence of these catalysts in order to study the catalytic properties of the zeolites. Zeolites catalysis the reaction providing the Markovnikov addition product. From structural point of view, there are some differences between the two classes of zeolites (mordenites and beta zeolites). From structural point of view, there are some differences among the two classes of zeolites (e.g., mordenites and beta zeolites): while beta zeolite has a three-dimensional channel system with 12-membered ring channels (0.76nm×0.64 nm), mordenites are characterized by a bi-dimensional channel system with straight 12-membered ring channels (0.65nm×0.70 nm) with crossed 8-membered ring channels (0.28nm×0.57 nm) [6]. 20A and 30A mordenites are inactive in the hydroamination reaction. Instead type beta zeolites have high activity. In this series, zeolite Beta 25 was the most active leading to a conversion of 23% and a selectivity of 70% in Markovnikov product after 24 hours at 90^{0}C. Increasing the temperature from 90^{0}C to 150^{0}C does not alter the order of business: zeolite Beta 30 showed higher catalytic activity compared to zeolite Beta 25 (74% conversion after 24 hours).

Adding a Lewis acid cocatalyst, $Sc(OTf)_3$, to the beta 25 and beta 30 zeolites leads to a decrease of the conversion. But the selectivities presented good yields in Markovnikov product. In the same time using pure $Sc(OTf)_3$ the conversion was superior to the BEA-25/$Sc(OTf)_3$ sau BEA-30/$Sc(OTf)_3$ mixtures, but still inferior to the simple zeolites.

Changing the substituent (para-H by para-NO_2) showed an improvement in conversion, this time only product obtained was the Markovnikov product. Adding $Sc(OTf)_3$ did not influence the conversion or selectivity.

Introduction p-Cl substituent to aniline led to a decrease in activity, while the reaction products resulting both. Adding $Sc(OTf)_3$ resulted in an increase in conversion and selectivity improvement in anti-Markovnikov product.

OH introduction to aniline in meta position also led to an increase in conversion compared to simple zeolites. In this case was not determined a major effect on selectivity. Adding $Sc(OTf)_3$ conversion increases, the selectivity maintaining the same.

Chapter 5 presents and discuss the behavior of a series of bis(oxazoline) metal(II) complexes that were supported on silica and carbon supports by non-covalent immobilisation using an ionic liquid. The catalytic performances of these solids were compared for the enantioselective Diels–Alder reaction between N-acryloyloxazolidinone and cyclopentadiene and the aldol-Mukaiyama reaction between methyl pyruvate and 1-methoxy-1-trimethylsilyloxypropene. In both reactions the enantioselectivity was strongly influenced by the choice of support displaying enantioselectivies (ee values) up to 40% higher than those conducted under homogeneous reaction conditions. The Diels-Alder reaction was catalyzed by a series of copper (II), magnesium (II) and zinc (II) triflates (10mol%) in homogeneous conditions, at room temperature, in molecular solvents (dichloromethane, diethyleter) and ionic liquids ($[C_2mim][NTf_2]$). Mukaiyama aldol-reaction was performed with a series of Lewis acids chiral catalysts (Cu (II) triflate and zinc (II) triflate 10mol%) under homogeneous conditions. A total conversion (100%) was recorded after only 1 minute at room temperature for catalysts in ionic liquid, while using dichloromethane and diethyl ether were obtained after moderate conversions after 15 minutes. All catalysts led to a higher *ee* in ionic liquid compared to reactions in dichloromethane and, in most cases, diethylether. In the presence of catalysts immobilized by SILP on silica and carbon there were obtained different results. The catalysts that had silica as a support furnished conversions and selectivities of 100% in aldol-Mukaiyama reaction.

As a conclusion the results obtained in this thesis are original and confirm the fact that the materials used are promising and can be applied in other synthesis reactions. The results obtained in the experimental study were published in different journals and have been the subject of various communications in international conferences.

Articles in international journals

1. Asymmetric Carbon-Carbon Bond Forming Reactions Catalysed by Metal(II) Bis(oxazoline) Complexes Immobilized using Supported Ionic Liquids- **published**/P.Goodrich,C.Hardacre, C. Paun,A. Ribeiro,S. Kennedy, M. J. V. Lourenco, H. Manyar, C. A. Nieto de Castro, **M. Besnea**, V. I. Parvulescu, *Adv. Synth. Catal*. 353 (2011) 995 – 1004
2. Heterogeneous amination of bromobenzene over titania-supported gold catalysts- **published**/ **Madalina Ciobanu,** Bogdan Cojocaru, Cristian Teodorescu, Florin Vasiliu, Simona M. Coman, Walter Leitner, Vasile I Parvulescu, *Journal of Catalysis* 296 (2012) 43-54

Communications in international and national conferences

1. "*New catalysts for hydroamination*", Sesiunea de Comunicări Științifice Studențesti, Ediția a VI-a, 07 Mai 2010
2. "*New catalysts for hydroamination*", Sesiunea de Comunicări Științifice Studențesti, Ediția a VII-a, 20 Mai 2011
3. "*Is TiO2 a stabilizing ligand for Au-nanoparticles?* ", Workshop: Flow Catalysis, St. Andrews, UK, 06-09Iunie 2011
4. "*New catalysts for hydroamination*", Workshop on Innovative Catalysis, Iunie 2011, Malta
5. "*New catalysts for hydroamination*", Școala de vară, Facultatea de Fizica, Romania,11-15 Iulie 2011

Posters

1. "New catalysts for hydroamination", RomCat, 23-26 Iunie 2010, Iași, România
2. "Catalytic Hydroamination of Unsaturated Carbon-Carbon Bonds", Workshop "Tendințe noi în știința materialelor" – 28-31 Martie 2012

Bibliography

1. F. Neatu, Z. Li, R. Richards, P.Y. Toullec, J.-P. Genet, K. Dumbuya, J. M. Gottfried, H.-P. Steinruck, V.I. Parvulescu, V. Michelet *Chem. Eur. J.* 14 (2008) 9412
2. S. R. Chemler, P. H. Fuller *Chem. Soc. Rev*. 36 (2007) 1153
3. M. Magureanu, N. B. Mandache, J. Hu, R. Richards, M. Florea, V.I. Parvulescu *Appl. Catal. B: Environmental* 76 (2007) 275
4. J. M. Moggia, V. G. Milt, M. A. Ulla, L. M. Cornaglia *Surf. Interface Anal.* 35 (2003) 216
5. H. Christensen, S. Kiil, K. Dam-Johansen *Organic Process Research & Development* 10 (2006) 762
6. Ch. Baerlocher, W. M. Meier, D. H. Olson *Atlas of Zeolite Framework Types. Fifth Revised Edition, Published on behalf of the Structure Commission of the International Zeolite Association*, Elsevier (2001)