Study of C-N, C-S, C-O Cross-Coupling Reactions and Chiral Copper(II) Complex for Asymmetric Catalysis

A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

by

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Guwahati 781039
April 2008

Dedicated

To

My Parents

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

Department of Chemistry

STATEMENT

I hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Chemistry, Indian Institute of Technology Guwahati, Guwahati, India under the supervision of Dr. Tharmalingam Punniyamurthy.

In keeping with the general practice of reporting scientific observations, due acknowledgement has been made wherever the work described is based on the findings of other investigators.

Guwahati   Laxmidhar Rout

April 2008

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

Department of Chemistry

CERTIFICATE

This is to certify that Mr. Laxmidhar Rout has been working under my supervision since December 2004. I am forwarding his thesis entitled "*Study of C-N, C-S, C-O Cross-Coupling Reactions and Chiral Copper(II) Complex for Asymmetric Catalysis*" being submitted for the Ph.D. degree of this Institute. I certify that he has fulfilled all the requirements according to the rules of this Institute, and regarding the investigations embodied in his thesis and this work has not been submitted elsewhere for a degree.

Guwahati
April 2008

Dr. Tharmalingam Punniyamurthy
Supervisor

INDIAN INSTITUTE OF TECHNOLOGYGUWAHATI

Department of Chemistry

COURSE CERTIFICATE

This is to certify that Mr. Laxmidhar Rout has satisfactorily completed all the courses required for the Ph.D. degree programme. These courses include:

CHM 601	Physical Methods in Chemistry
CHM 605	Applied Crystallography
CHM 621	New Reagents for Organic Synthesis
CHM 632	Advanced Group Theory & Application

Mr. Laxmidhar Rout has successfully completed his Ph.D. qualifying examination in November 2005.

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Dr. Anil Kumar Saikia
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ACKNOWLEDGEMENT

I am extremely grateful to my supervisor Prof. Tharmaligam Punniyamurthy for his patient guidance, encouragement and valuable suggestions in research topics throughout my research period. His friendly encouragement and creation of positive confidence among me was the most important aspect to be successful in the art of organic synthesis. As supervisor, his insight, observation, way of training and useful discussions were extremely beneficial to my future goal. I am proud of working with my supervisor for last three years. He will remain as one of the best teacher ever I came across in my whole academic career. I shall remain indebted to him forever.

I owe my sincere thanks to my lab colleagues Velusamy, Sridhar, Akhilagunta, Suribabu, Prasenjit, Priyanka and Sakthivel for their pleasant company during my research period. I am also thankful to my all friends (Bibhuti, Nihar, Himansu, Safique, Hrushi, Joyprada, Susanta, Sudhansu, Martha, Jugal, Monoranjan, Promod, Subash, Biswa, Naresh, Sisir, Rozy, Nameeta) for their support and encouragement.

I am greatly indebted to Anasuya (Mata) for her unfounding help during my research. I am grateful to my teachers Prof. S. Jena, G. C. Pradhan, P. Mohanty, A. C. Das, P.K. Sahoo, S. P. Rout and Aditya Panda for their helpful suggestions.

I acknowledge the Indian Institute of Technology, Guwahati for providing institute fellowship for the entire period of the Ph.D. programme.

Finally my sincere thanks go to my parents, sisters and brothers for their sustained help and encouragement in all my academic endeavors. I feel deeply indebted to them for whatever I have achieved so far.

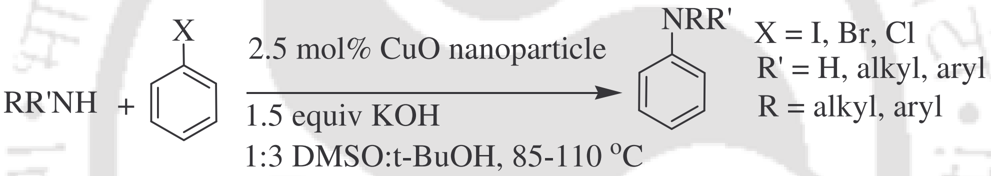
Laxmidhar Rout

Abstract

The thesis contains four chapters. Chapter I focuses on the *C-N* cross-coupling reactions, while Chapters II and III deal with *C-S* and *C-O* cross-coupling reactions. Chapter IV describes the synthesis, structure and application of a stereoregular chiral copper(II) coordination polymer for asymmetric catalysis.

1. *N*-Arylation of Aryl Iodides with Nitrogen Nucleophiles

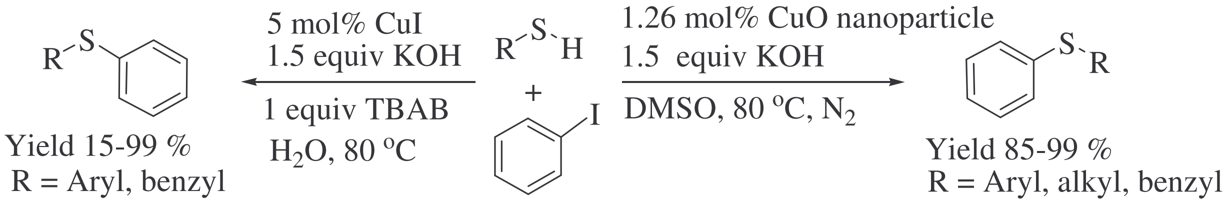
The formation of *C-N* bonds by cross-coupling reactions represent powerful means for the preparation of numerous compounds in biological, pharmaceutical and material sciences. This chapter elaborates the use of CuO nanoparticle for the amination of aryl iodides (Scheme 1). It is a heterogeneous process and functions under ligand-free condition. Both aryl and alkyl amines undergo reaction with high yields.



Scheme 1

2. *S*-Arylation of Aryl Iodides with Sulfur Nucleophiles

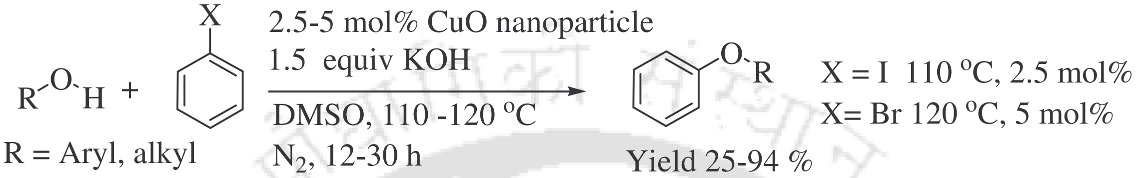
Methods for the formation of *C-S* bonds are indispensable tools in synthetic chemistry. Their importance stems from the prevalence of *C-S* bonds in many molecules that are of biological, pharmaceutical and material interest. This chapter is divided into two sections. Section I focuses on CuO nanoparticle catalyzed *C-S* cross-coupling reactions in DMSO and Section II shows the use of CuI/TBAB for the *C-S* cross-coupling reactions in water (Scheme 2).



Scheme 2

3. *O*-Arylation of Aryl Halides with Oxygen Nucleophiles

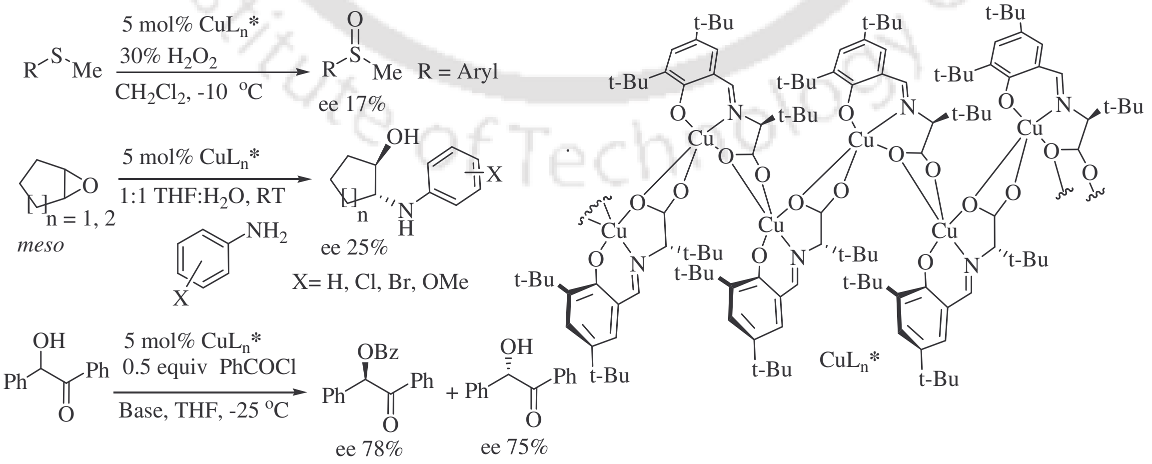
Aryl ethers and oxygen heterocycles are common structures in many pharmaceutically and agriculturally important compounds. Transition-metal-catalyzed formation of *C-O* bonds by cross-coupling reactions constitutes powerful method for the preparation of these compounds. This chapter describes CuO nanoparticle catalyzed *C-O* cross-coupling of aryl iodide and -bromide with hydroxy compounds (Scheme 3).



Scheme 3

4. Synthesis, Crystal Structure and Application of Chiral Copper(II) Coordination Polymer for Asymmetric Catalysis

Asymmetric catalysis provides an effective strategy for the preparation of optically active molecules from pro-chiral compounds. This chapter describes the synthesis, crystal structure and application of chiral copper(II) coordination polymer for asymmetric sulfoxidation with aqueous H_2O_2, opening of *meso*-epoxides with aniline and asymmetric benzoylation reactions (Scheme 4).



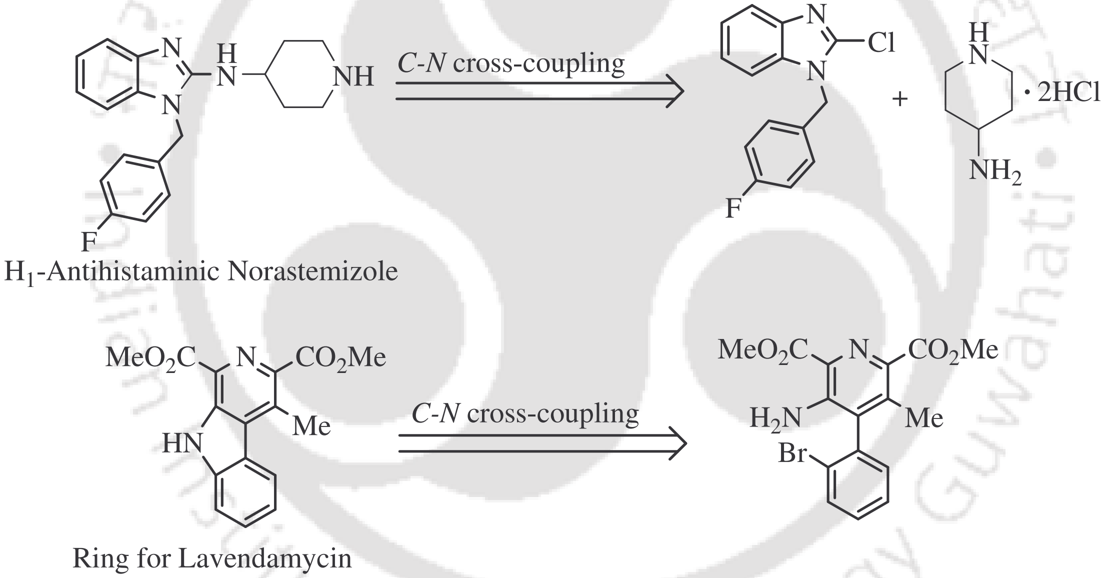
Scheme 4

Contents

Chapter I

N-Arylation of Aryl Iodides with Nitrogen Nucleophiles

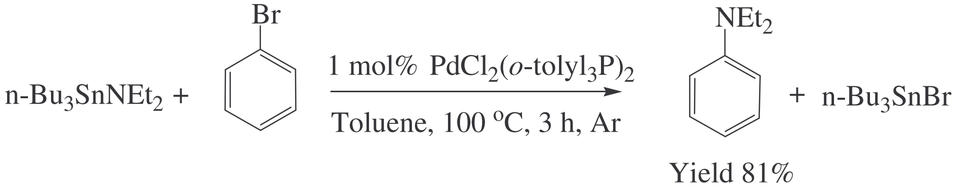
The formation of *C-N* bonds by cross-coupling reactions represents powerful means for the preparation of numerous compounds in pharmaceutical, material and biological sciences (Scheme 1).[1] However, the traditional methods used for this purpose are often required harsh reaction conditions such as high temperature (>150 ^{o}C) and stoichiometric or greater amount of copper reagents which on scale-up leads to problem of waste disposal.[2] To overcome these drawbacks, considerable attention has been recently focused on this reaction to develop catalytic systems.[3] From an industrial standpoint, these studies are attractive since the cost and environmental impact (*E*-factor) of the processes can be lowered.[4]



Scheme 1

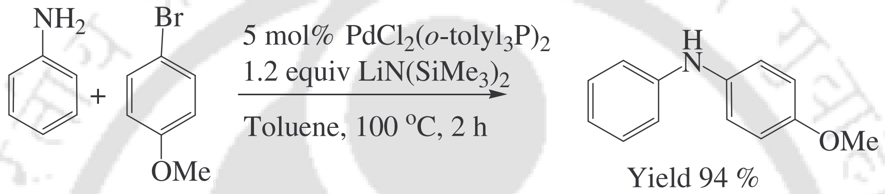
1.1.1 Palladium Catalysts

Palladium based catalytic systems have been considerably studied for the cross-coupling of amines with aryl halides.[5] In 1983, Migita and co-workers first reported the *C-N* cross-coupling of *N*,*N*-diethylamino-tributyltin with aryl bromide using $PdCl_2(o\text{-tolyl}_3P)_2$ under argon atmosphere (Scheme 2).[5a] Under these conditions, aryl chlorides and aryl iodides donot undergo cross-coupling reactions.



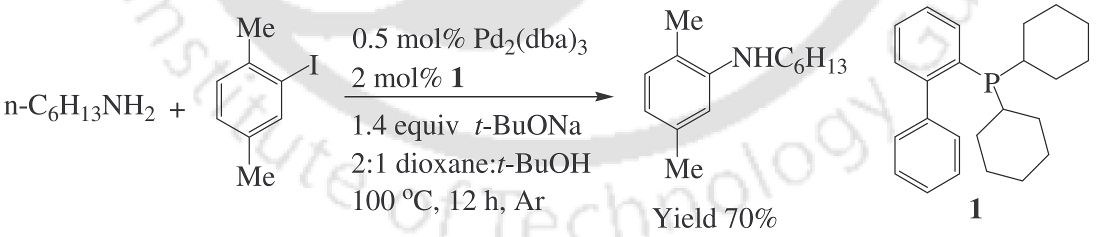
Scheme 2

After nearly a decade, Louie and Hartwig used the above catalyst for the coupling of amines with aryl bromides (Scheme 3).[5b] It is an improved version of Migita's reaction and avoids the necessity of forming tin amides and disposing of tin halide.

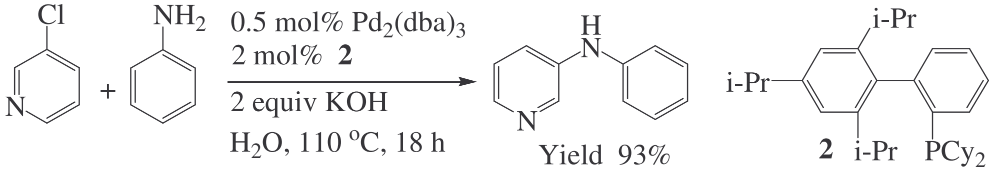


Scheme 3

Ali and Buchwald used palladium(0) complex generated *in situ* from $Pd_2(dba)_3$ [dba = *trans*, *trans*-dibenzylidene acetone] and ligand **1** for the coupling of aryl iodides with amines (Scheme 4).[5c] This group also further demonstrated the coupling of amines with aryl chlorides by using palladium(0) complex generated *in situ* from $Pd_2(dba)_3$ and ligand **2** in water (Scheme 5).[5d]

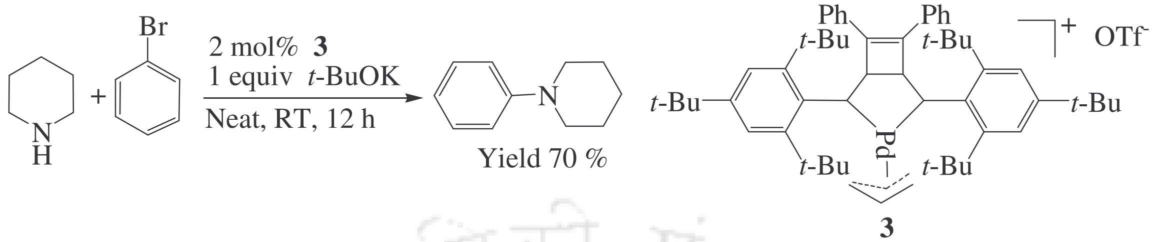


Scheme 4



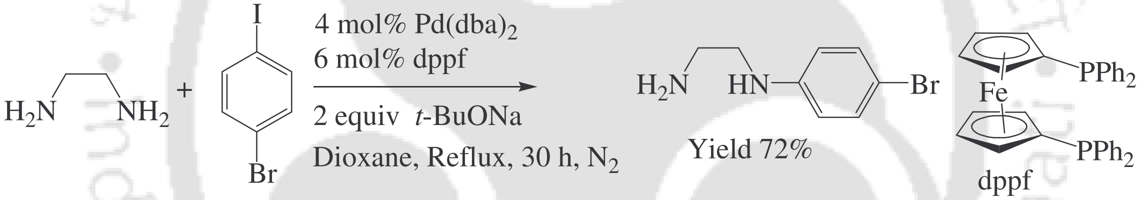
Scheme 5

The air-stable (*π*-allyl) palladium complex **3** is used for the coupling of amines with aryl bromides in the presence of *t*-BuOK under solvent free conditions (Scheme 6).[5e] This reaction takes place at ambient temperature with good yield.



Scheme 6

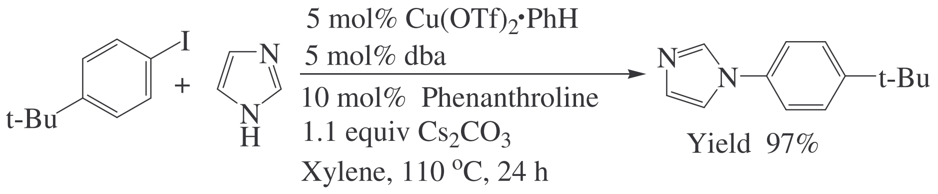
$Pd_2(dba)_3(dppf)$ is used for the chemoselective monoarylation of polyamines with aryl halides in the presence of *t*-BuONa in dioxane under reflux conditions (Scheme 7).[5f] For an example, ethylene diamine is selectively monoarylated with 4-bromo-1-iodobenzene in 72% yield.



Scheme 7

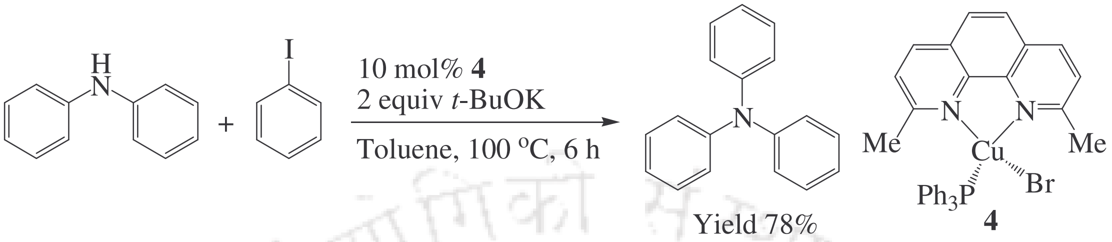
1.1.2 Copper Catalysts

Copper complexes bearing electron rich ligands are extensively studied for the *C-N* cross-coupling of amines with aryl halides.[6] These catalytic systems are more attractive compared to the palladium based systems. The coupling of azoles with aryl iodides is accomplished using $(CuOTf)_2$-1,10-phenanthroline in high yield (Scheme 8).[6a] This reaction functions at 110 °C in the presence of Cs_2CO_3 and addition of dba is crucial for its success.



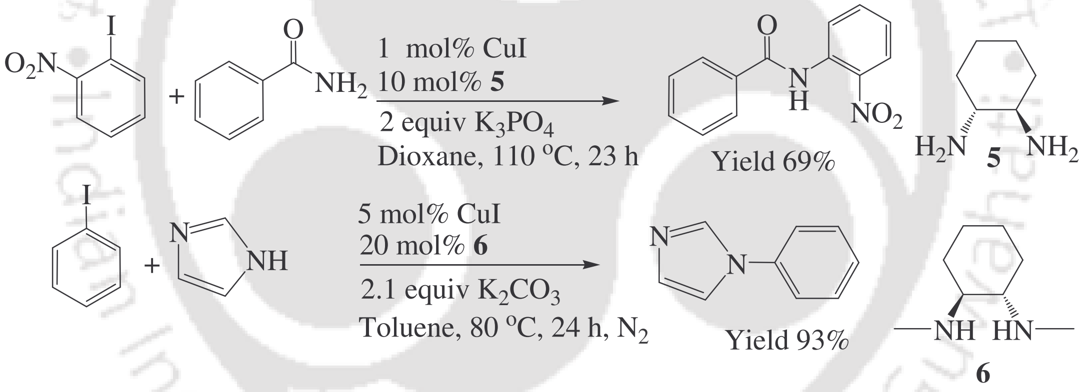
Scheme 8

Copper(I) complex **4** is used for the cross-coupling of aryl amines with aryl iodides at 100 °C in the presence of *t*-BuOK (Scheme 9).[6b] These reaction conditions are also suitable for the coupling of aryl halides with phenols and *C*-*C* coupling reactions when *t*-BuOK is replaced by Cs_2CO_3.

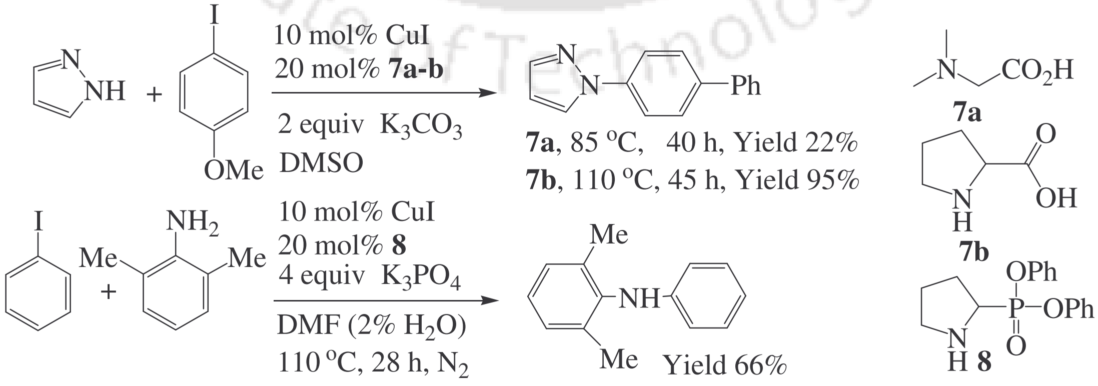


Scheme 9

By the combined use of CuI and optically active 1,2-diamines, the amidation and amination of aryl halides with nitrogen nucleophiles are subsequently accomplished (Scheme 10).[6c-d] Of the various 1,2-diamines studied, **5** and **6** have provided the best results.



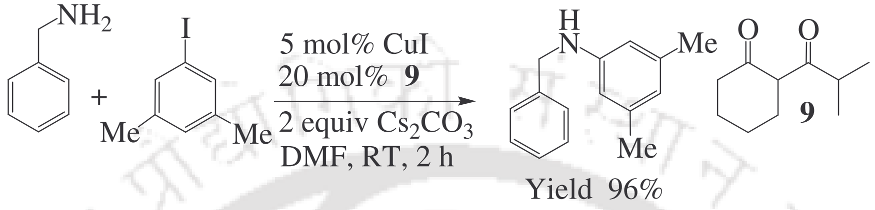
Scheme 10



Scheme 11

The coupling of aryl halides with amines and azoles is also demonstrated using CuI and amino acid based ligands **7a-b**[6e] and **8**[6f] (Scheme 11). These reaction conditions are also suitable for *C-P* and *C-O* cross coupling reactions.

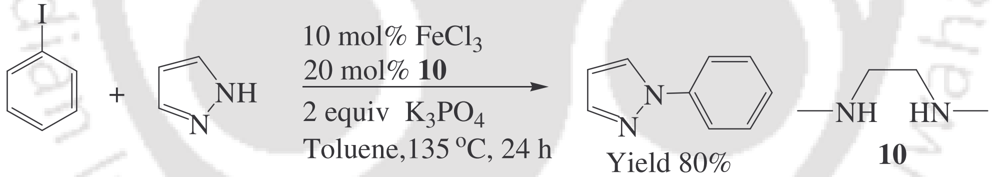
The complex formed from CuI and 1,3-dicarbonyl compounds are used for the amination of aryl halides at ambient temperature (Scheme 12).[6g] Of the various 1,3-dicarbonyl compounds screened, ligand **9** is exhibited the best results.



Scheme 12

1.1.3 Iron Catalyst

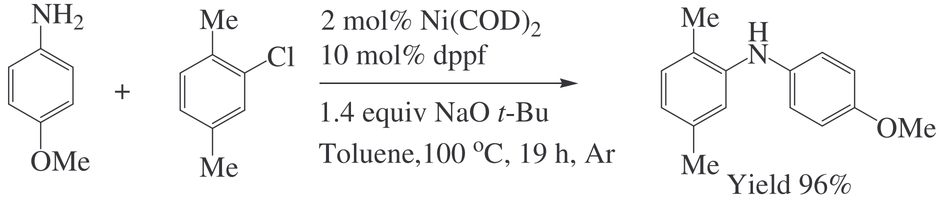
Following the Pd and Cu based catalytic systems, FeCl$_3$ with 1,2-diamine is used for coupling of azoles and amides with aryl iodides (Scheme 13).[7] Under these conditions anilines don't undergo coupling reaction. This procedure is attractive from environmental view point.



Scheme 13

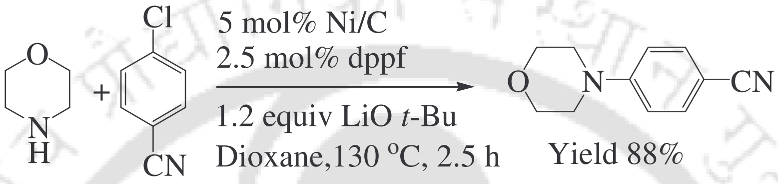
1.1.4 Nickel Catalysts

Nickel based catalytic systems are studied for the coupling of aryl chlorides with amines.[8] Aryl chlorides are converted to aniline derivatives using complex formed from Ni(COD)$_2$ (COD = 1,5-cyclooctadiene) and dppf in the presence of NaO*t*-Bu (Scheme 14).[8a] Electron-rich or electron-poor aryl chlorides, as well as chloropyridine derivatives, can be coupled with primary and secondary amines in moderate to excellent yields.



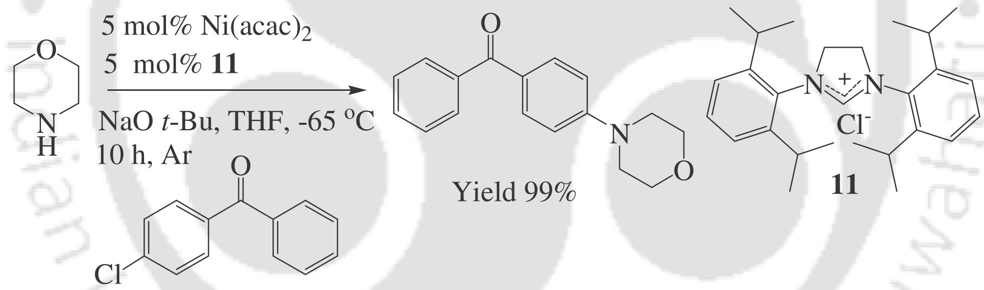
Scheme 14

Ueda and Lipshutz demonstrated the use of Ni(0)/C with dppf in the presence of *t*-BuOLi for coupling of aryl chloride with amines (Scheme 15).[8c]



Scheme 15

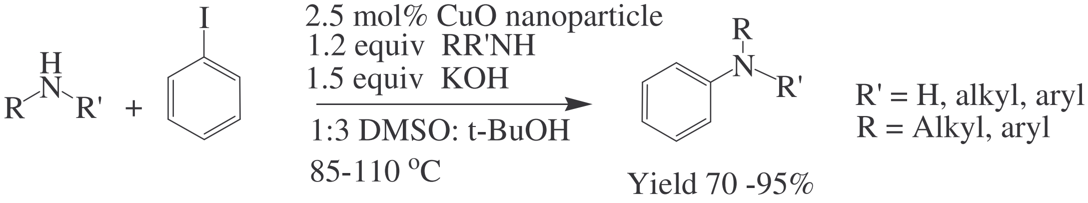
Fort and co-workers used nickel(0) with carbene for coupling of aryl chlorides with amines in the presence of *t*-BuONa (Scheme 16).[8d]



Scheme 16

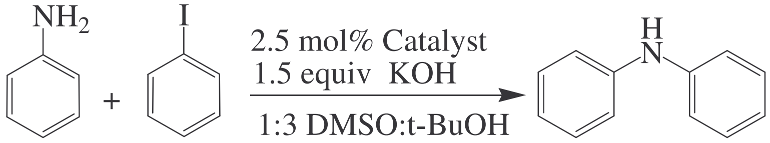
1.2 Present Study

The use of colloidal metal nanoparticle for organic synthesis has been intensive in recent years.[9] Because of their high surface area and catalytic activity. This section describes CuO nanoparticle catalyzed coupling of nitrogen nucleophiles with aryl iodides (Scheme 17). It is ligand-free and catalyst is recyclable without loss of activity.



Scheme 17

Table 1. Reaction of Aniline with Iodobenzene using Different Copper Sources



Entry	Catalyst	Yield (%)[a]
1	$CuSO_4 \cdot 5H_2O$	46
2	$Cu(OAc)_2 \cdot 1H_2O$	33
3	CuO	35
4	CuO nanoparticle	95

[a] Catalyst (2.5 mol%), aniline (2.5 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred for 24 h at 110 °C in 1:3 DMSO : t-BuOH (2 mL).

Table 2. Reaction of Aniline with Iodobenzene: The Effect of Base and Solvent

Entry	Solvent	Base	Yield (%)[a]
1	Toluene	KOH	<10
2	Dioxane	KOH	10
3	DMF	KOH	<5
4	1: 3 DMSO:t-BuOH	KOH	95
5	t-BuOH	KOH	65
6	1:3 DMSO:t-BuOH	Cs_2CO_3	nr
7	1:3 DMSO:t-BuOH	K_2CO_3	nr
8	1: 3 DMSO:t-BuOH	Pyridine	nr

[a] CuO nanoparticle (2.5 mol%), aniline (2.5 mmol), iodobenzene (2 mmol), base (3 mmol) and solvent (2 mL) were stirred at 110 °C for 24 h.

nr = no reaction observed.

First, the reaction of aniline with iodobenzene studied as standard substrate to optimize the reaction conditions. Of the copper sources, CuO nanoparticle, $CuSO_4 \cdot 5H_2O$, $Cu(OAc)_2 \cdot 1H_2O$ and CuO, the former provided the best results (Table 1). In bases, KOH was more effective compared to pyridine, Cs_2CO_3 and K_2CO_3 (Table 2). Among the solvents screened, DMSO, DMF, dioxane, toluene and t-BuOH, the reaction was more effective in 1:3 mixture of DMSO and t-BuOH. Iodobenzene exhibited greater reactivity compared to bromo- and chlorobenzene (Table 3).

Table 3. Reaction of Aniline with Iodo-, Bromo- and Chlorobenzene

Entry	Aryl halide	Yield(%)[a]
1	Iodobenzene	95
2	Bromobenzene	30
3	Chlorobenzene	<5

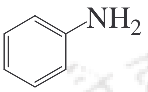
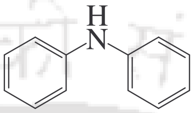
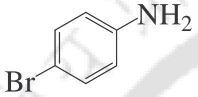
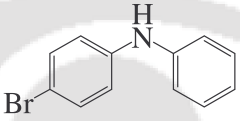
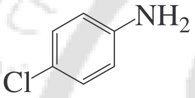
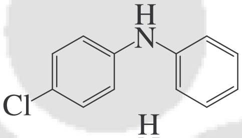
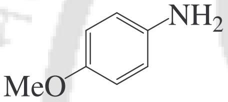
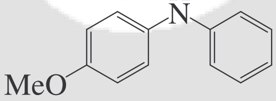
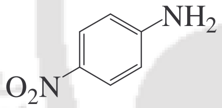
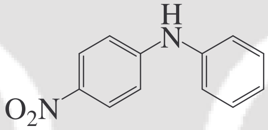
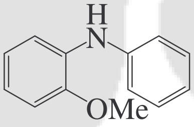
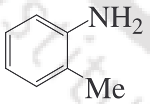
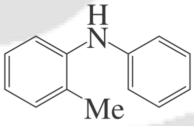
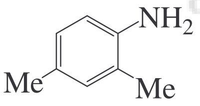
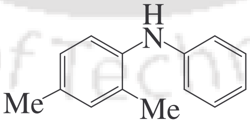
[a] CuO nanoparticle (2.5 mol%), aniline (2.5 mmol), aryl halide (2 mmol) and KOH (3 mmol) were stirred at 110 °C in 1:3 mixture of DMSO : t-BuOH (2 mL).

To study the scope of the procedure, the reaction of aryl amines with iodobenzene was next studied (Table 4). Anilines with 4-chloro-, 4-bromo-, 4-methoxy- and 4-nitro substituents underwent reaction in 70-94% yield. Similar results observed with 2-methyl, 2-methoxy- and 2, 4-dimethylaniline. Aniline having electron donating groups showed greater reactivity compared to those with electron withdrawing groups.

The coupling of alkyl amines with aryl iodide further studied. Benzylamine, furfurylamine, *n*-butylamine and cyclohexylamine underwent reaction in 85-93% yield (Table 5). Similar reactivity was observed with pyrrolidine, piperidine and morpholine affording the cross-coupled products in high yields.

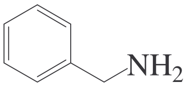
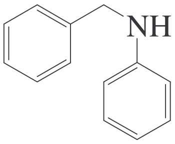
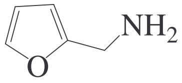
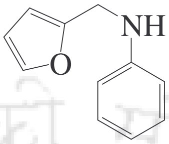
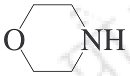
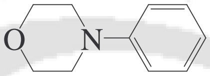
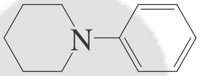
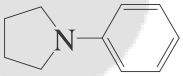
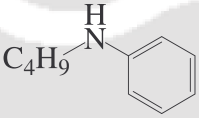
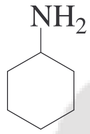
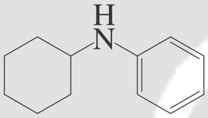
Finally, the coupling of aryl *N*-heterocyclic compounds with iodobenzene studied (Table 6). Pyrrole, indole, imidazole, 2-methyl imidazole and benzimidazole underwent reaction with 76-94% yield. It is a heterogeneous process and CuO nanoparticles can be recycled without loss of activity (Table 7). After the completion of the reaction of aniline with iodobenzene, the CuO nanoparticles was recovered by centrifugation and recycled for the fresh reaction of aniline with iodobenzene. The reaction occurred to afford the desired diphenylamine with high yield. This process was repeated up to three runs and no loss of activity was observed.

Table 4. The Cross-Coupling of Aryl Amines with Iodobenzene

Entry	Amine	Product	Time (h)	Yield (%)[a]
1			24	95
2			12	83
3			11	92
4			6	94
5			24	70
6			9	88
7			10	85
8			10	78

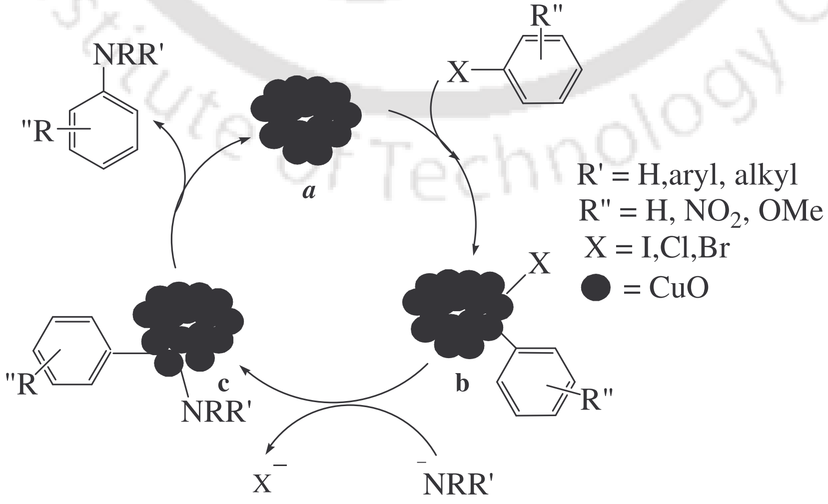
[a]CuO nanoparticle (2.5 mol%), amines (2.5 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred at 110 °C in 1:3 DMSO : t-BuOH (2 mL).

Table 5. Reaction of Alkyl Amines with Iodobenzene

Entry	Amine	Product	Time (h)	Yield (%)[a]
1			10	90
2			17	85
3[b]			10	89
4[b]			9	90
5[b]			8	93
6	n-$C_4H_9NH_2$		13	91
7			7	93

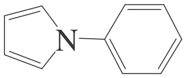
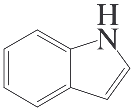
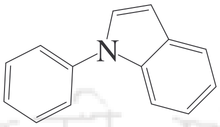
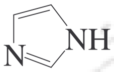
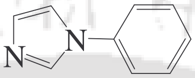
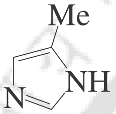
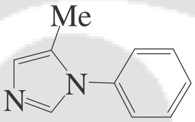
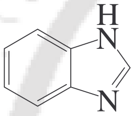
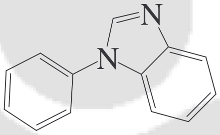
[a] CuO nanoparticle (2.5 mol%), amines (2.5 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred at 110 °C in 1:3 DMSO : t-BuOH (2 mL).

[b] 85 °C used.



Scheme 18. Proposed Catalytic Cycle

Table 6. Reaction of Aryl *N*-Heterocyclic Compounds with Iodobenzene

Entry	Aryl *N*-Hetrocyclics	Product	Time (h)	Yield (%)[a]
1			12	93
2			12	94
3			15	91
4			24	76
5			20	85

[a] CuO nanoparticles (2.5 mol%), aryl *N*-heterocyclic compound (2.5 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred at 110 °C in 1:3 DMSO : t-BuOH (2 mL).

Table 7. Recyclability of the CuO Nanoparticles: Coupling of Aniline with Iodobenzene

Run	Recoverability (%) of CuO nanoparticle	Diphenylamine (%)[a]
1	95	95
2[b]	89	90
3[b]	81	87

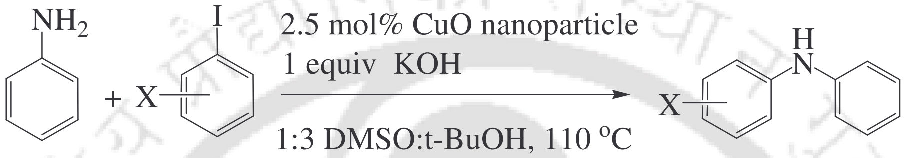
[a] CuO nanoparticle (2.5 mol%), aniline (2.5 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred at 110 °C for 24 h in 1:3 DMSO : t-BuOH (2 mL).

[b] Recovered catalyst.

Mechanism

To reveal the mechanism, the reaction of substituted aryl iodides with aniline was studied. Aryl iodide having electron donating group showed lesser reactivity compared to that bearing electron withdrawing substituent (Table 8). These results clearly reveal that the CuO nanoparticle catalyzed reaction takes by oxidative addition followed by reductive elimination process (Scheme 18). Stabilization of the CuO nanocluster ***a*** followed by oxidative addition with aryl iodide can generate intermediate ***b***. The intermediate ***b*** can undergo reaction with amine ion to give intermediate ***c*** by nucleophilic substitution. The intermediate ***c*** by reductive elimination can complete the catalytic cycle.

Table 8. Reaction of Substituted Iodobenzenes with Aniline



Entry	X	Yield (%)[a]
1	MeO	17
2	H	30
3	NO_2	93

[a] CuO nanoparticle (2.5 mol%), aniline (2.5 mmol), aryl iodide (2 mmol) and KOH (3 mmol) were stirred for 6 h at 110 °C in 1:3 DMSO : t-BuOH (2 mL).

Recyclability of CuO Nanoparticles

After the reaction is complete, the mixture was concentrated in rotavapour to remove t-BuOH. It was treated with ethyl acetate and water. The aqueous solution was then centrifuged with 10,000 rpm for an hour to provide CuO nanoparticles. It was, after drying under vacuum, reused for the fresh reaction of aniline with iodobenzene for three recycles.

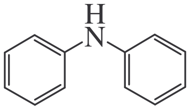
In conclusion, the *C-N* cross-coupling of nitrogen nucleophiles with aryl iodides using CuO nanoparticles is described. Aryl, alkyl and *N*-heterocyclic amines can be cross-coupled with aryl iodides in high yields. These reactions are effective with less concentration of the catalysts. The CuO nanoparticles can be recycled without loss of activity.

Experimental Section

General. Amines, bromobenzene (98%), chlorobenzene (99%), iodobenzene (98%) and CuO nanoparticle (particle size 33 nm and surface area 29 m^2/g) were purchased from Sigma-Aldrich and copper (II) salts were purchased from Merck. NMR spectra (400 MHz for ^1H and 100 MHz for ^{13}C) were recorded using DRX-400 varian spectrometer using $CDCl_3$ as solvent and Me_4Si as internal standard. FT-IR spectra were recorded on Nicolet 410 spectrometer. Flash column chromatography was performed on silica gel (230-400 mesh) using ethyl acetate and hexane as eluent. Melting points were determined using Buchi B-540 melting point apparatus and uncorrected. Centrifugation was done using SIGMA 3K30 Sartorius machine.

General Procedure for *C-N* Cross-Coupling Reaction

To a stirred solution of amine (2.5 mmol), aryl iodide (2 mmol) and KOH (2 mmol) in 1:3 DMSO: t-BuOH (2 mL), CuO nanoparticle (2.5 mol%) was added. The solution was heated at 110 °C for the appropriate time. The progress of the reaction was monitored by TLC. The reaction mixture was then cooled to room temperature and treated with ethyl acetate (10 mL) and water (3 mL). The aqueous layer was separated and extracted with ethyl acetate (3 x 5 mL). The combined organic solution, after successively washed with brine (3 x 5 mL) and water (1 x 5 mL), dried (Na_2SO_4) and passed through a short pad of celite. Evaporation of the solvent provided a residue which was purified on silica gel column chromatography using ethyl acetate and hexane as eluent.



Diphenylamine. Aniline (2.5 mmol, 232 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 24 h to afford diphenylamine as pale yellow solid in 95% (321 mg) yield.

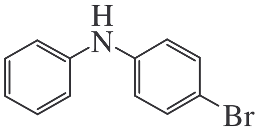
Mp: 52 °C.

^1H NMR ($CDCl_3$, 400 MHz) δ 7.27-7.22 (m, 4H), 7.07-7.04 (d, *J* = 7.2 Hz, 4H), 6.93-6.89 (m, 2H), 5.69 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 143.33, 129.55, 121.21, 118.01.

IR (KBr): ν 3404, 3380, 3040, 1582, 1513, 1493, 1457, 1307 cm^{-1}.

Anal Calcd for $C_{12}H_{11}N$: C, 85.17; H, 6.55; N, 8.28. Found C, 85.20; H, 6.56; N, 8.30.



_N_-(4-Bromophenyl)aniline. 4-Bromoaniline (2.5 mmol, 430 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 12 h to afford *N*-(4-bromophenyl)aniline as light yellow solid in 83% (410 mg) yield.

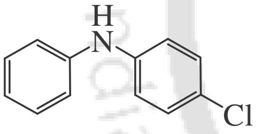
Mp: 88 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.35-7.25 (m, 5H), 7.08-6.92 (m, 4H), 5.69 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 147.23, 145.34, 129.76, 129.48, 128.01, 126.57, 117.57, 114.30.

IR (KBr): ν 3399, 3039,1579, 1495, 1479, 1310, 1070 cm^{-1}.

Anal Calcd for $C_{12}H_{10}NBr$: C, 58.09; H, 4.06; N, 5.65. Found: C, 58.08; H, 4.08; N, 5.64.



_N_-(4-Chlorophenyl)aniline. 4-Chloroaniline (2.5 mmol, 318 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 11 h to afford *N*-(4-chlorophenyl)aniline as colorless solid in 92% (374 mg) yield.

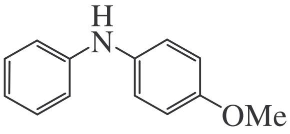
Mp: 73 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.27-7.16 (m, 5H), 7.03-6.91 (m, 4H), 5.66 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) 147.29, 146.30, 132.38, 129.66, 121.35, 119.21, 115.43.

IR (KBr): ν 3406, 2927, 1587, 1509, 1485, 1310, 1088, 843, 809, 752, 693 cm^{-1}.

Anal Calcd for $C_{12}H_{10}NCl$: C, 70.77; H, 4.95; N, 6.88. Found: C, 70.80; H, 4.96; N, 6.90.



_N_-(4-Methoxyphenyl)aniline. 4-Methoxyaniline (2.5 mmol, 307 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5

mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 6 h to afford *N*-(4-methoxyphenyl)aniline as colorless solid in 94% (374 mg) yield.

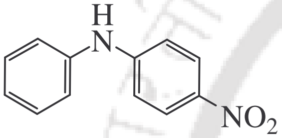
Mp: 105 °C.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.42 (d, *J* = 8.4 Hz, 2H), 7.24-7.12 (m, 5H) 6.90 (d, *J* = 8.4 Hz, 2H), 5.51 (s, 1H), 3.81 (s, 3H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 153.54, 145.79, 135.58, 129.10, 123.42, 120.10, 115.15, 55.32.

IR (KBr): ν 3065, 2955, 2927, 1651, 1417, 1318, 1300, 1194, 1168, 1125, 749, 696 cm^{-1}.

Anal Calcd for $C_{13}H_{13}NO$: C, 78.36; H, 6.58; N, 7.03. Found: C, 78.40; H, 6.59; N, 7.07.



N-(4-Nitrophenyl)aniline. 4-Nitroaniline (2.5 mmol, 345 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 24 h afford *N*-(4-nitrophenyl)aniline as yellow powder in 70% (299 mg) yield.

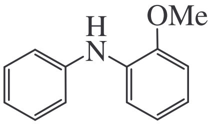
Mp: 134 °C.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 8.11 (d, *J* = 9.2 Hz, 2H), 7.38 (t, *J* = 8.0 Hz, 2H) 7.20-7.12 (m, 3H), 6.93 (d, *J* = 7.6 Hz, 2H), 6.34 (s, 1H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 151.45, 138.24, 137.57, 129.72, 127.64, 125.71, 123.42, 114.00.

IR (KBr): ν 3338, 1601, 1580, 1467, 1271,1249 cm^{-1}.

Anal Calcd for $C_{12}H_{10}N_2O_2$: C, 67.28; H, 4.71; N, 13.08. Found: C, 67.30; H, 4.69; N, 13.12.



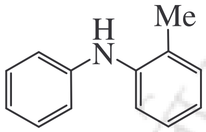
N-(2-Methoxyphenyl)aniline. 2-Methoxyaniline (2.5 mmol, 305 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 9 h to afford *N*-(2-methoxyphenyl)aniline as yellow oil in 88% (350mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.32-7.26 (m, 3H), 7.16-7.12 (m, 2H), 7.03 (t, *J* = 7.2 Hz, 1H), 6.94-6.55 (m, 3H) 6.19 (s, 1H), 3.91 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 148.37, 143.39, 132.38, 129.65, 121.85, 119.21, 118.48, 115.92, 110.57, 58.58.

IR (neat): ν 3379, 2956, 1592, 1500, 1456, 1442, 1310, 1230, 1164, 1128, 1023 cm^{-1}.

Anal Calcd for $C_{13}H_{13}NO$: C, 78.36; H, 6.58; N, 7.03. Found: C, 78.40; H, 6.60; N, 7.06.



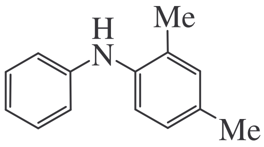
***N*-(2-Methylphenyl)aniline.** 2-Methylaniline (2.5 mmol, 232 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 10 h to afford *N*-(2-methylphenyl)aniline as colorless liquid in 85% (311 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.25-7.17 (m, 5H), 7.13 (t, *J* = 6.8 Hz, 1H), 6.95-6.88 (m, 3H) 5.48 (s, 1H), 2.24 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 143.39, 142.89, 130.43, 129.72, 127.64, 125.78, 121.85, 119.21, 118.48, 17.63.

IR (KBr): ν 3384, 2951, 2917, 2857, 1591, 1492, 1459, 1415, 1294, 1259, 1102, 1089, 1031, 801, 746, 691 cm^{-1}.

Anal Calcd for $C_{13}H_{13}N$: C, 85.21; H, 7.15; N, 7.64. Found: C, 85.25; H, 7.14; N, 7.63.



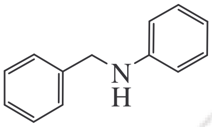
***N*-(2,4-Dimethyl phenyl)phenylamine.** 2,4-Dimethylaniline (2.5 mmol, 302 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 10 h to afford *N*-(2,4-dimethyl phenyl)phenylamine as colorless oil in 78% (307 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.19-7.13 (m, 2H), 7.07 (d, *J* = 8.0 Hz, 1H) 6.96 (s, 1H), 6.90 (d, *J* = 8.0 Hz, 1H), 6.88-6.75 (m, 3H), 5.25 (s, 1H), 2.23 (s, 3H), 2.15 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 143.33, 139.54, 129.38, 124.52, 121.32, 117.57, 116.77, 21.15, 20.75.

IR (neat): ν 3402, 3390, 3016, 2961, 2923, 2851, 1596, 1495, 1311, 1262, 1097, 1028, 875, 801, 746, 691 cm^{-1}.

Anal Calcd for $C_{14}H_{15}N$: C, 85.24; H, 7.66; N, 7.10. Found: C, 85.25; H, 7.65; N, 7.14.



***N*-Phenylbenzylamine.** Benzylamine (2.5 mmol, 267 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 10 h to afford *N*-phenylbenzylamine as colorless solid in 90% (329 mg) yield.

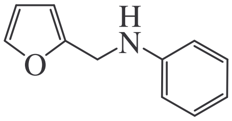
Mp: 34 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.34-7.22 (m, 5H), 7.15 (t, *J* = 7.2 Hz, 2H), 6.71 (t, *J* = 7.6 Hz, 1H), 6.61 (d, *J* = 7.63 Hz, 2H), 4.31 (s, 2H), 4.09 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 149.56, 139.54, 130.08, 129.05, 128.70, 127.38, 118.32, 113.31, 48.56.

IR (KBr): ν 3384, 3003, 1600, 1498, 1321 cm^{-1}.

Anal Calcd for $C_{13}H_{13}N$: C, 85.21; H, 7.15; N, 7.64. Found: C, 85.25; H, 7.16; N, 7.67.



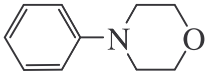
***N*-(Phenyl)furfurylamine.** Furfurylamine (2.5 mmol, 242 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 17 h to afford *N*-(phenyl)furfurylamine as colorless oil in 85% (294 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.33 (s, 1H), 7.16 (t, *J* = 8.0 Hz, 2H), 6.73-6.64 (m, 3H), 6.29 (s, 1H), 6.21 (s, 1H), 4.29 (s, 2H), 4.01 (s, 1H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 153.28, 148.56, 142.13, 129.44, 118.23, 113.35, 110.54, 107.20, 41.63.

IR (neat): ν 3281, 3027, 1609, 1515, 1452, 761, 734 cm^{-1}.

Anal Calcd for $C_{11}H_{10}NO$: C, 76.28; H, 6.40; N, 8.09. Found: C, 76.30; H, 6.41; N, 8.10.



***N*-Phenylmorpholine.** Morpholine (2.5 mmol, 220 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 85 °C for 6.5 h to afford *N*-phenylmorpholine as colorless solid in 89% (291 mg) yield.

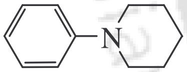
Mp: 55 °C.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.28 (t, *J* = 8.0 Hz, 2H), 6.90-6.84 (m, 3H), 3.85 (t, *J* = 4.8 Hz, 4H), 3.14 (t, *J* = 4.8 Hz, 4H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 151.46, 129.39, 120.28, 115.92, 67.14, 49.55.

IR (KBr): ν 2922, 2854, 1601, 1458, 1377 cm^{-1}.

Anal Calcd for $C_{10}H_{13}NO$: C, 73.59; H, 8.03; N, 8.58. Found: C, 73.60; H, 8.04; N, 8.57.



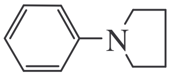
***N*-Phenylpiperidine.** Piperidine (2.5 mmol, 212 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 85 °C for 9 h to afford *N*-phenylpiperidine as colorless oil in 90% (290 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.24-7.20 (m, 2H), 6.93-6.91 (m, 2H), 6.80 (t, *J* = 7.2 Hz, 1H), 3.19 (t, *J* = 5.6 Hz, 4H), 1.71-1.66 (m, 4H), 1.58-1.53 (m, 2H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 152.82, 129.48, 119.09, 117.57, 51.45, 29.55, 26.25.

IR (neat): ν 2926, 2857, 1603, 1457, 1379 cm^{-1}.

Anal Calcd for $C_{11}H_{15}N$: C, 81.94; H, 9.38; N, 8.69. Found: C, 81.95; H, 9.37; N, 8.70.



***N*-Phenylpyrrolidine.** Pyrrolidine (2.5 mmol, 157 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3

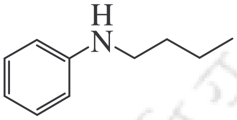
DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 85 ^{o}C for 8 h to afford *N*-phenylpyrrolidine as colorless oil in 93% (273 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.18-7.13 (m, 2H), 6.58 (t, *J* = 7.2 Hz, 1H), 6.50 (d, *J* = 8.4 Hz, 2H), 3.20 (t, *J* = 6.8 Hz, 4H), 1.94-1.90 (m, 4H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 139.33, 129.01, 115.21, 111.49, 47.43, 25.34.

IR (neat): ν 2926, 2827, 1643, 1427, 1369, 1103 cm^{-1}.

Anal Calcd for $C_{10}H_{13}N$: C, 81.59; H, 8.90; N, 9.51. Found: C, 81.62; H, 8.89; N, 9.52.



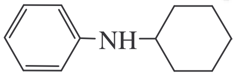
***N*-Phenylbutylamine.** Butylamine (2.5 mmol, 180 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 ^{o}C for 13 h to afford *N*-phenylbutyl amine as colorless oil in 91% (271 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.16–7.12 (m, 2H), 6.66 (t, *J* = 7.2 Hz, 1H), 6.59 (d, *J* = 8.4 Hz, 2H), 3.51(s, 1H), 3.10-3.06 (m, 2H), 1.61-1.54 (m, 2H), 1.45-1.36 (m, 2H), 0.95-0.91 (m, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 129.41, 117.25, 112.86, 43.85, 31.86, 20.50, 14.12.

IR (neat): ν 3400, 2954, 2907, 2871, 1601, 1497, 1301, 1205, 1141, 1089, 781 cm^{-1}.

Anal Calcd for $C_{10}H_{15}N$: C, 80.48; H, 10.13; N, 9.39. Found: C, 80.50; H, 10.14; N, 9.40.



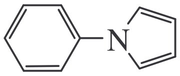
***N*-Cyclohexylaniline.** Cyclohexylamine (2.5 mmol, 247 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 ^{o}C for 7 h to afford *N*-cyclohexylaniline as colorless oil in 93% (325 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15-7.07 (m, 2H), 6.66-6.56 (m, 3H), 5.24 (s, 1H), 3.24-3.21 (m, 1H), 2.05-2.03 (m, 2H), 1.77-1.72 (m, 2H), 1.66-1.61 (m, 1H), 1.40-1.10 (m, 5H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 147.29, 129.57, 116.77, 113.31, 53.13, 33.04, 26.62, 25.17.

IR (neat): ν 3407, 3311, 3068, 2930, 1615, 1396, 1256, 1091, 1031, 803 cm^{-1}.

Anal Calcd for $C_{12}H_{17}N$: C, 82.23; H, 9.78; N, 7.99. Found: C, 82.26; H, 9.80; N, 8.04.



***N*-Phenylpyrrole.** Pyrrole (2.5 mmol, 167 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 12 h to afford *N*-phenylpyrrole as colorless solid in 93% (265 mg) yield.

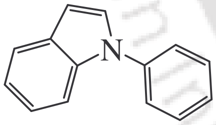
Mp: 62 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.73 (d, *J* = 7.6 Hz, 2H), 7.46-7.26 (m, 3H), 7.14-7.11 (m, 2H) 6.38-6.37 (m, 2H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 137.66, 130.43, 129.73, 127.64, 125.73, 120.70, 119.49, 110.57.

IR (KBr): ν 3375, 2960, 2929, 1624, 1404, 1262, 1089, 1053, 1026, 798 cm^{-1}.

Anal Calcd for $C_{10}H_9N$: C, 83.88; H, 6.34; N, 9.78. Found: C, 83.91; H, 6.33; N, 9.80.



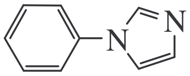
***N*-Phenylindole.** Indole (2.5 mmol, 292 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 12 h to afford *N*-phenylindole as colorless oil in 94% (362 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.78 (d, *J* = 7.6 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 1H), 7.57-7.56 (m, 3H), 7.41-7.40 (m, 2H), 7.30-7.25 (m, 3H), 6.58 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 139.95, 135.97, 129.76, 129.48, 128.09, 126.57, 124.49, 122.52, 121.30, 120.53, 110.67, 103.73.

IR (neat): ν 3340, 3049, 2917, 2851, 1495, 1456, 1347, 1330, 1303, 1231, 1212, 1133, 1072, 1009, 771, 714, 694, 609 cm^{-1}.

Anal Calcd for $C_{14}H_{11}N$: C, 87.01; H, 5.74; N, 7.25. Found: C, 87.03; H, 5.75; N, 7.27.



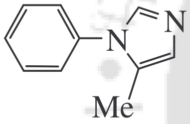
***N*-(Phenyl)imidazole.** Imidazole (2.5 mmol, 170 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 15 h to afford *N*-(phenyl)imidazole as yellow oil in 91% (262 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.87 (s, 1H), 7.50-7.47 (m, 2H), 7.40-7.37 (m, 3H), 7.29 (s, 1H), 7.21 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 137.47, 135.76, 130.46, 130.06, 127.70, 121.66, 118.45, 107.38.

IR (neat): ν 3268, 3394, 2963, 2927, 2871, 1596, 1495, 1459, 1380, 1259, 1155, 1091, 1031, 803, 749, 696 cm^{-1}.

Anal Calcd for $C_9H_8N_2$: C, 74.98; H, 5.59; N, 19.43. Found: C, 74.99; H, 5.58; N, 19.50.

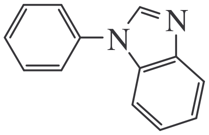


***N*-(Phenyl)-5-methyl-imidazole.** 2-Methylimidazole (2.5 mmol, 205 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 24 h to afford *N*-(phenyl)-5-methyl-imidazole as colorless oil in 76% (240 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.43-7.35 (m, 5H), 7.22-7.20 (m, 3H), 6.96 (s, 1H), 6.93 (s, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ 129.65, 128.37, 127.72, 125.68, 120.83, 13.89.

IR (neat): ν 3384, 3116, 2963, 2925, 2856, 1596, 1500, 1415, 1300, 1259, 1176, 1135, 1094, 1028, 795, 765, 696, 672 cm^{-1}.

Anal Calcd for $C_{10}H_{10}N_2$: C, 75.92; H, 6.37; N, 17.71. Found: C, 75.95; H, 6.38; N, 17.75.



***N*-(Phenyl)benzimidazole.** Benzimidazole (2.5 mmol, 295 mg), iodobenzene (2 mmol, 406 mg), KOH (2 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and 1:3 DMSO :t-BuOH (2 mL) were subjected to the reaction condition described in the general procedure at 110 °C for 20 h to afford *N*-(phenyl)benzimidazole as colorless solid in 85% (330 mg) yield.

Mp: 96 °C.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 8.16 (s, 1H), 7.90-7.87 (m, 1H), 7.57-7.43 (m, 6H), 7.34-7.30 (m, 2H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 142.63, 130.29, 128.41, 124.30, 124.07, 123.23, 120.63, 110.76.

IR (KBr): ν 3404, 2964, 2937, 1619, 1597, 1500, 1478, 1456, 1421, 1289, 1259, 1231, 1089, 1037, 1020, 801, 787, 754, 746, 694 cm^{-1}.

Anal Calcd for $C_{13}H_{10}N_2$: C, 80.39; H, 5.19; N, 14.42. Found: C, 79.08; H, 4.97; N, 28.01.

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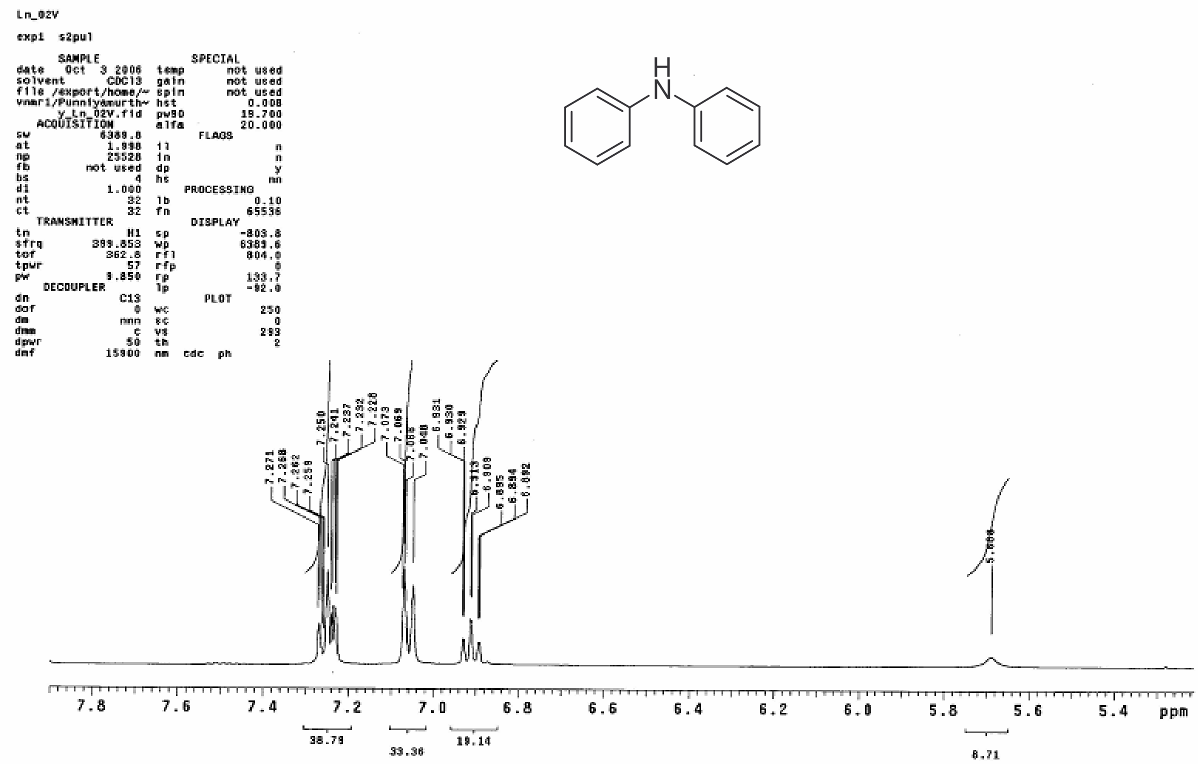

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sw            6389.8           FLAGS
at             1.998  il                n
np             25528  in                n
fb          not used  dp                y
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d1             1.000        PROCESSING
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ct                32  fn            65536
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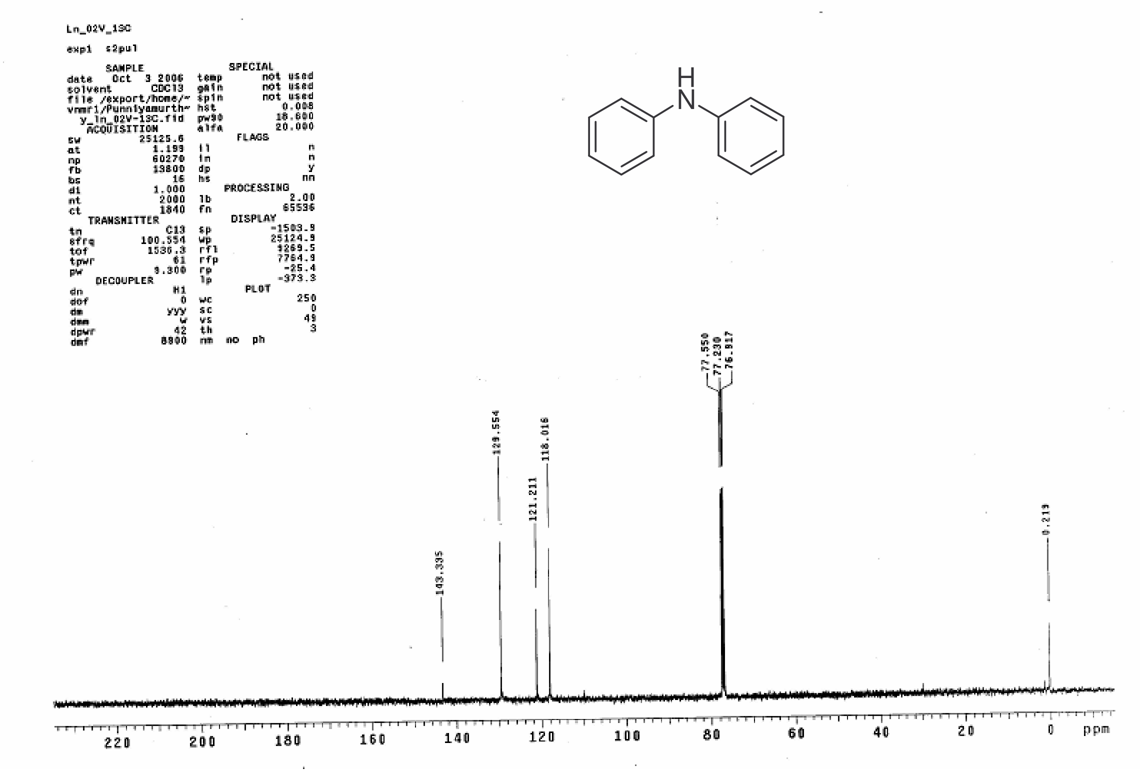

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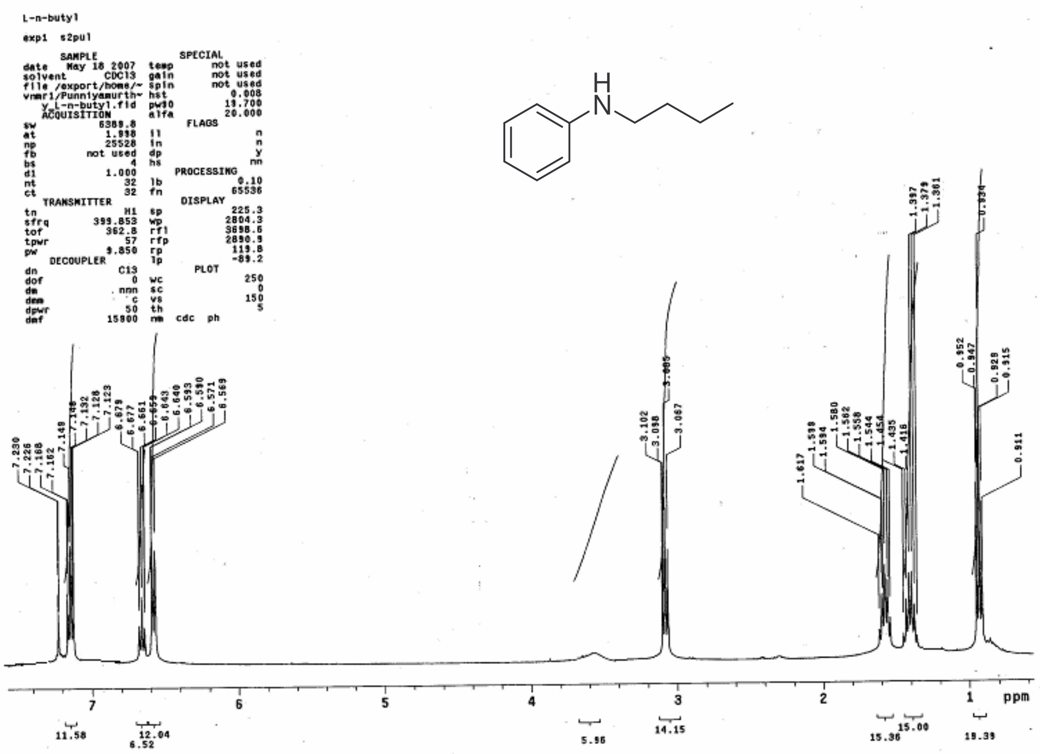

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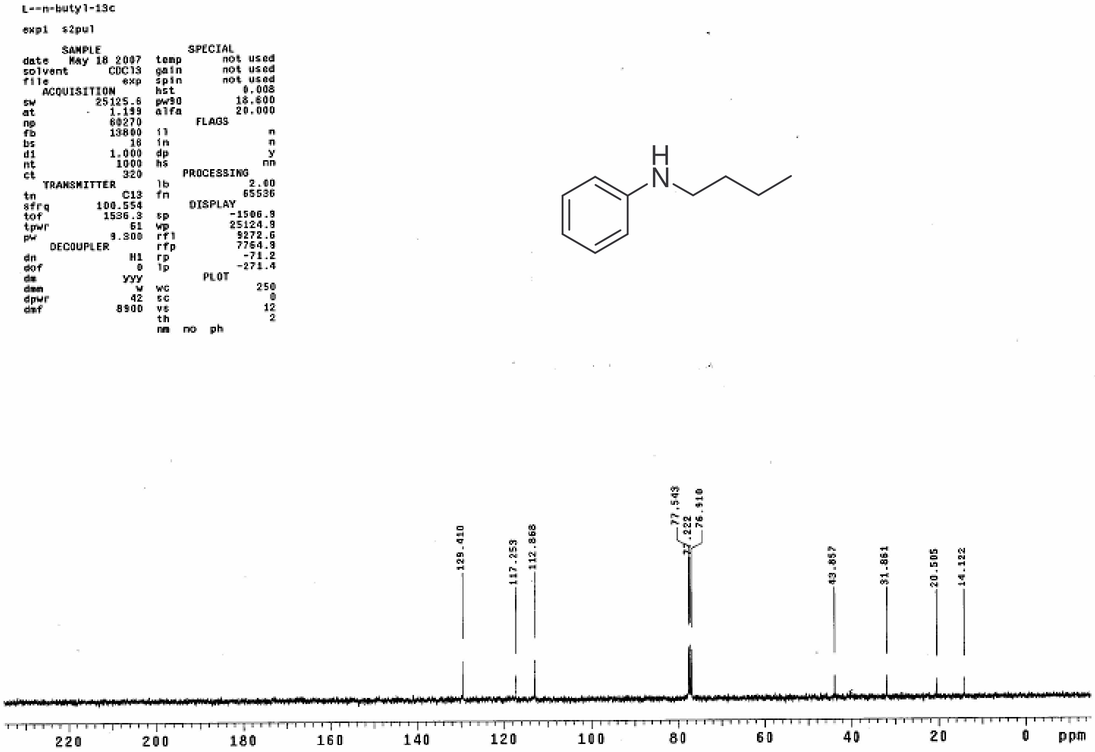

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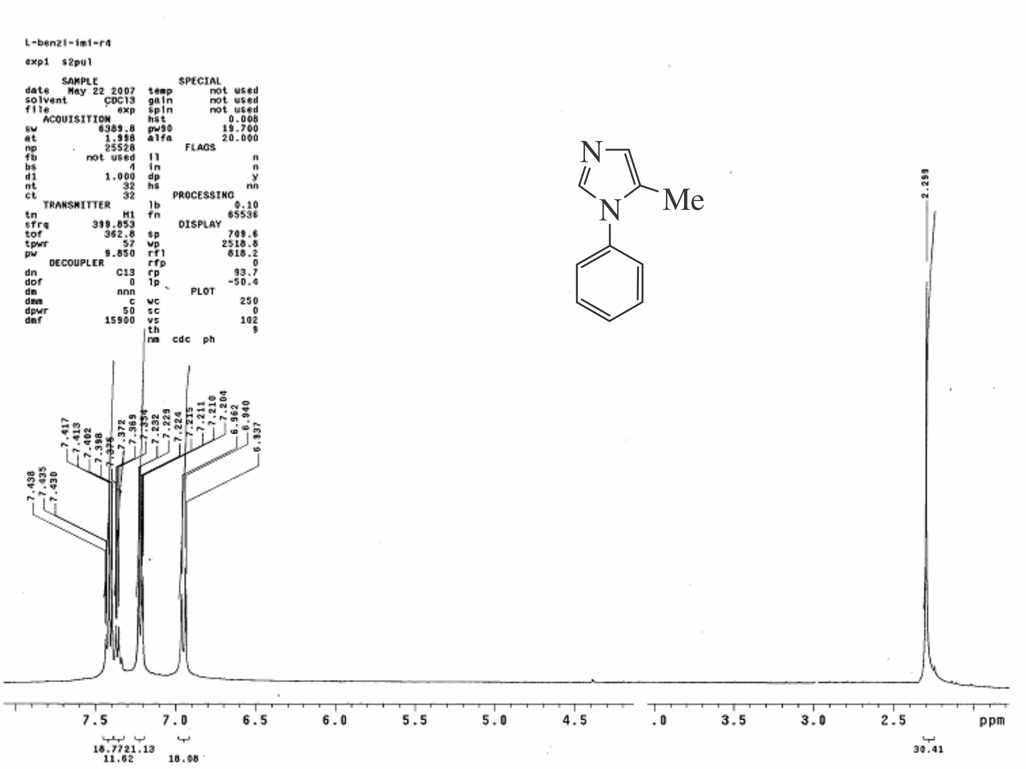
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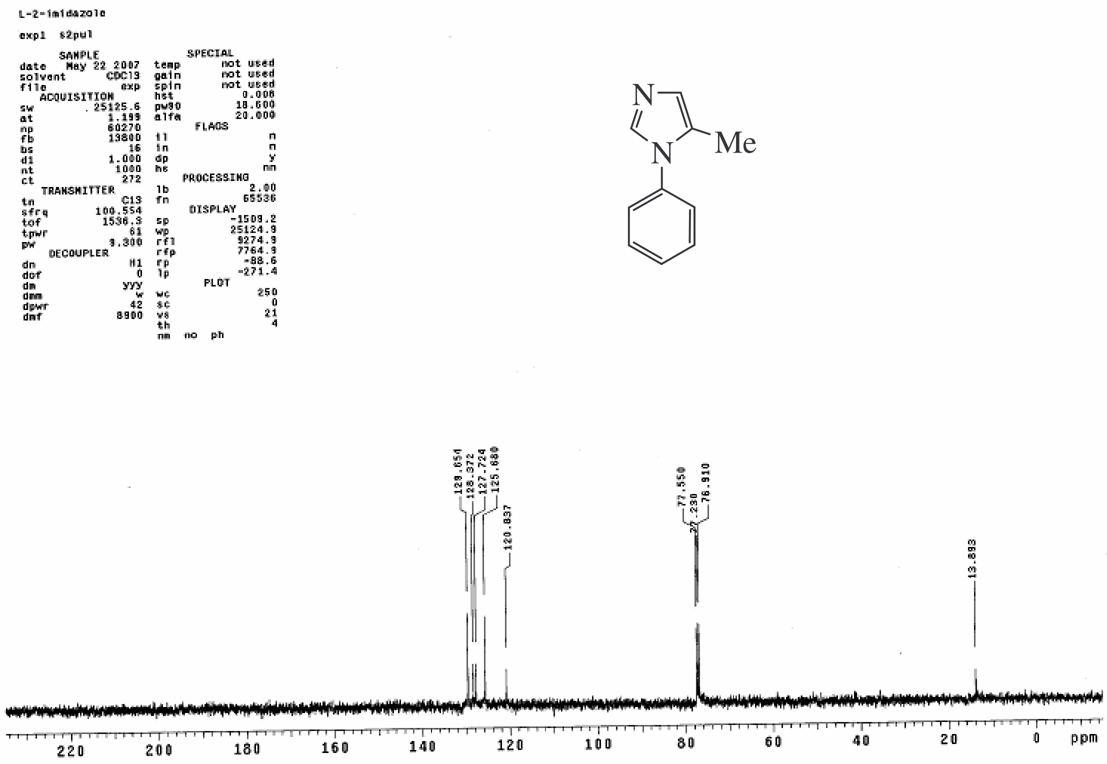
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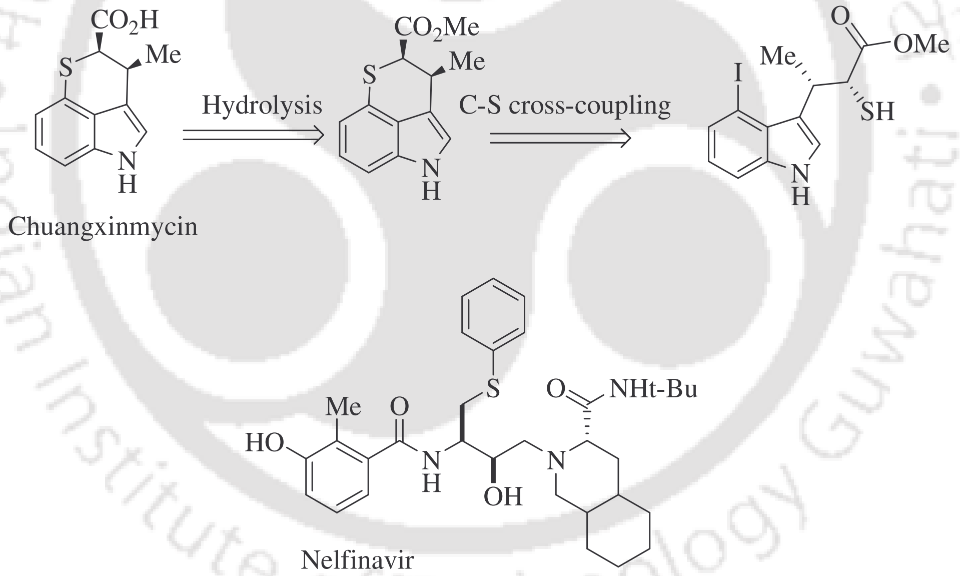
ppm

Chapter II

S-Arylation of Aryl Halides with Sulfur Nucleophiles

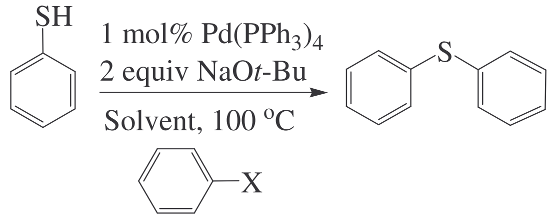
The cross-coupling of thiols with aryl halides is an important reaction in organic synthesis. The products, substituted sulfides, serve as building blocks for the synthesis of sulfur containing compounds in medicinal, material and biological sciences (Scheme 1).[1] Traditional methods for the formation of *C-S* bonds often require harsh reaction conditions. For examples, use of polar solvents such as HMPA, temperature around 200 °C, reduction of sulfones or sulfoxides by DIBAL-H or $LiAlH_4$[2] and designing ligands with *ortho* carbonyl groups that are both electron withdrawing and capable of chelating copper limit their application in industry. Thus, considerable attention has been recently focused to develop catalytic systems for this reaction.



Scheme 1

2.1.1 Palladium Catalysts

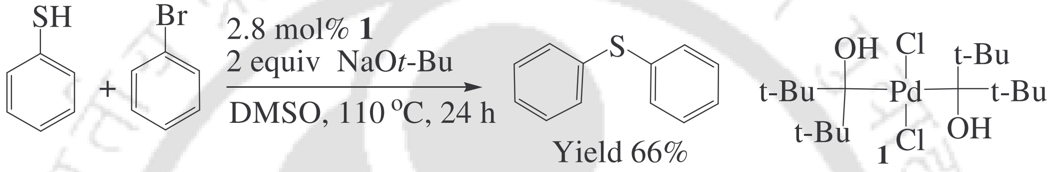
Palladium based catalysts are widely studied for *C-S* cross-coupling reactions.[3,4] In 1980, Migita and co-workers first reported the cross-coupling of thiols with aryl halides using $Pd(PPh_3)_4$ in the presence of NaO*t*-Bu in polar solvents such as refluxing ethanol or DMSO (Scheme 2).[3] Aryl iodide and –bromide are compatible with this catalytic system affording the cross-coupled products in high yield.



Solvent	X	Time (h)	Yield (%)
DMSO	I	3	22
DMSO	Br	10	82
t-BuOH	I	3	100
t-BuOH	Br	10	100
t-BuOH	Cl	10	trace

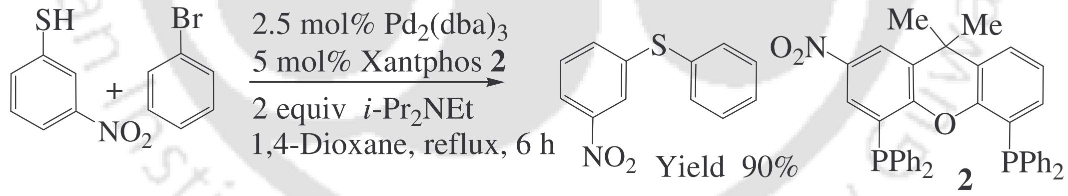
Scheme 2

The coupling of aryl chlorides and -bromides with thiols is subsequently studied using palladium(II) complex **1** in the presence of NaO*t*-Bu (Scheme 3).[4a] These reaction conditions are also suitable for the reactions of aryl halides with amines and alkenes.

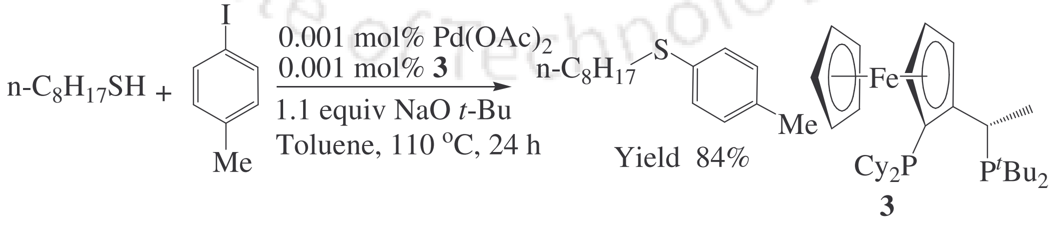


Scheme 3

Itoh and Mase reported the cross-coupling of thiols with aryl bromides by the combined use of $Pd_2(dba)_3$ and xantphos **2** in the presence of *i*-Pr_2NEt in 1,4-dioxane (Scheme 4).[4c] These reaction conditions are also compatible for the coupling of aryl chlorides with thiols.



Scheme 4

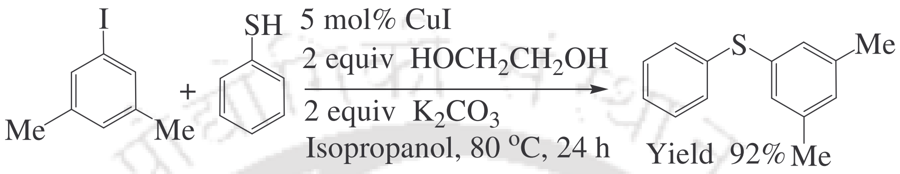


Scheme 5

Hartwig and co-workers showed the coupling of thiols with aryl halides using $Pd(OAc)_2$ and ligand **3** in the presence of NaO*t*-Bu in toluene (Scheme 5).[4d] Under these conditions, aryl iodides and –bromides undergo reaction with high turnovers.

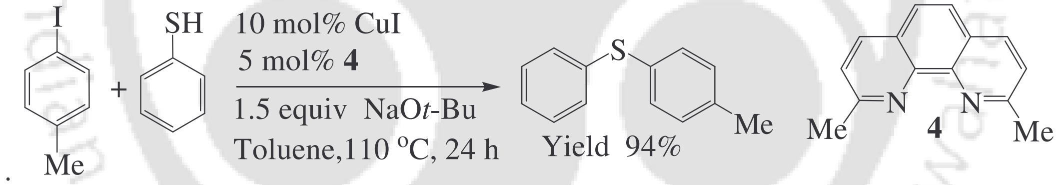
2.1.2 Copper Catalysts

Following the palladium catalyzed reactions, copper based catalytic systems are considerably studied for *C*-*S* cross-coupling reactions.[5] CuI-1,2-ethylene glycol is used for the coupling of thiols with aryl iodides in the presence of K_2CO_3 in 2-propanol (Scheme 6).[5b] The reaction of aryl iodides having electron withdrawing and –donating groups is demonstrated.



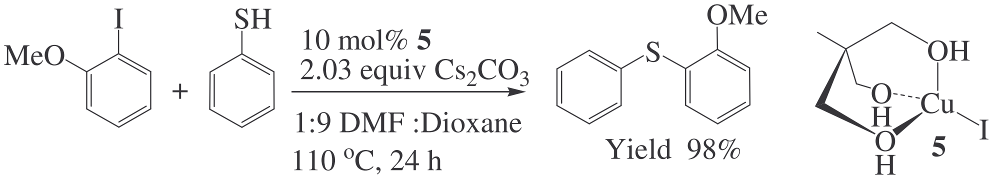
Scheme 6

Venkataraman and co-workers showed the coupling of aryl thiols with aryl iodides using CuI and neocuproine **4** in the presence of NaO*t*-Bu in toluene (Scheme 7).[5a] Using this procedure the coupling of thiophenol with 4-methyliodobenzene is accomplished in 94% yield.



Scheme 7

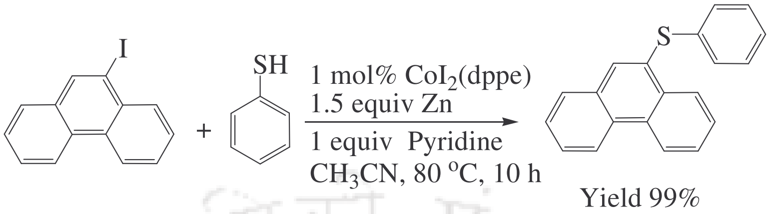
More recently, copper(I) complex **5** is used for the coupling of aromatic thiols with aryl iodides in the presence of Cs_2CO_3 in 1:9 DMF:dioxane (Scheme 8).[5i] These reaction conditions are also effective for *C*-*O* cross-coupling reactions.



Scheme 8

2.1.3 Cobalt Catalyst

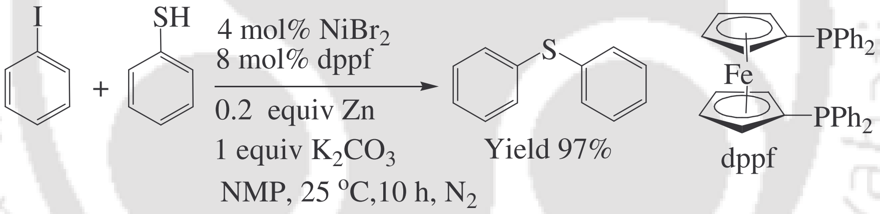
By the combined use of $CoI_2(dppe)_2$ and Zn powder, the cross-coupling of thiols with aryl iodides and –bromides is accomplished in the presence of pyridine (Scheme 9).[6] Under these conditions thiophenol is coupled with 9-iodophenanthrene in 99% yield.



Scheme 9

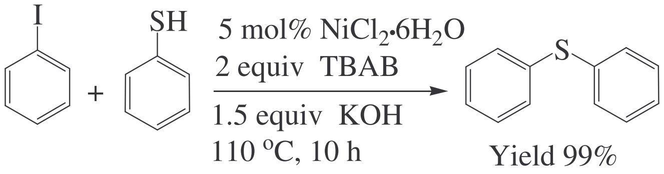
2.1.4 Nickel Catalysts

Few studies are focused on nickel catalysed *C-S* cross coupling reactions.[7] The combination of $NiBr_2$-dppf [dppf =1,1'-bis(diphenylphosphino ferrocene)] and zinc is used for coupling of aromatic thiols with aryl iodides and –bromides in the presence of K_2CO_3 in *N*-methyl-2-pyrrolidone at ambient temperature (Scheme 10).[7a]



Scheme 10

More recently, we reported the coupling of thiols with aryl iodides using $NiCl_2{\cdot}6H_2O$ in TBAB (TBAB = tetrabutylammonium bromide) (Scheme 11).[7e] In these reactions, the products are separated from the solid material by extraction with diethyl ether and the insoluble catalyst can be recycled without loss of activity.



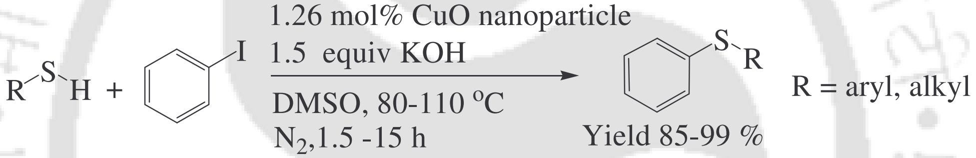
Scheme 11

2.2 Present Study

This section describes *C-S* cross-coupling of aryl halides with thiols employing CuO nanoparticles[8] and CuI/TBAB systems.

2.2.1 CuO Nanoparticle Catalyzed Reactions

Following the success with the *C-N* cross-coupling reactions, the CuO nanoparticles were further studied for the *C-S* cross-coupling reactions (Scheme 12). The reaction conditions were optimized by studying the coupling of thiophenol with iodobenzene as model substrate. The reaction occurred to afford the desired *C-S* cross-coupled product in 95% yield when the substrates were stirred at 80 °C in the presence of 1.26 mol% of CuO nanoparticles and 1.5 equiv of KOH in DMSO. Of the copper(II) sources screened, CuO nanoparticles, $CuSO_4 \cdot 5H_2O$. $Cu(OAc)_2 \cdot 1H_2O$ and CuO, the former provided the best results (Table 1). The reaction with KOH was superior to that used K_2CO_3, Et_3N, pyridine and Cs_2CO_3 affording the cross-coupled product in high yield (Table 2). Among



Scheme 12

Table 1. Cross-Coupling of Thiophenol with Iodobenzene with Different Copper(II) Sources

Entry	Catalyst	Time (h)	Yield (%)[a]
1	CuO nanoparticle	10	95
2	$CuSO_4 \cdot 5H_2O$	7	35
3	$Cu(OAc)_2 \cdot 2H_2O$	7	33
4	CuO	7	40

[a]Catalyst (1.26 mol%), thiophenol (2 mmol), iodobenzene (2.2 mmol) and KOH (3 mmol) were stirred at 80 °C in DMSO (2 mL).

Table 2. Reaction of Thiophenol with Iodobenzene: Effect of Base, Solvent and Temperature

Entry	Solvent	Base	Temp.(°C)	Time (h)	Yield (%)[a]
1	DMSO	KOH	RT	18	40
2	DMSO	K_2CO_3	RT	18	25[b]
3	*i*-PrOH	KOH	RT	18	20[b]
4	*i*-PrOH	KOH	80	10	75
5	DMSO	K_2CO_3	80	15	45
6	DMF	KOH	80	10	5
7	Dioxane	KOH	80	15	0
8	Toluene	KOH	80	10	<5
9	DMSO	NEt_3	80	10	0
10	DMSO	Pyridine	80	10	0

[a] CuO nanoparticle (1.26 mol%), thiophenol (2 mmol), iodobenzene (2.2 mmol) and base (3 mmol) were stirred in appropriate solvent (2 mL).

[b] 5-10% Disulfide obtained.

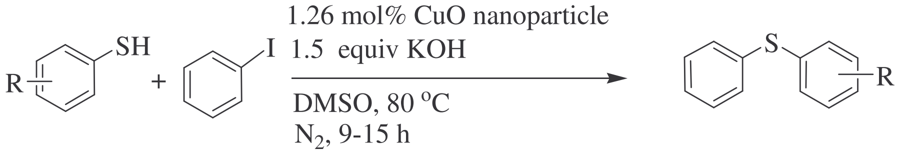
Table 3. Reaction of Thiophenol with Different Aryl Halides

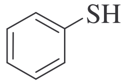
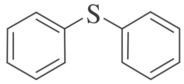
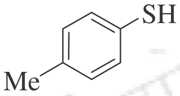
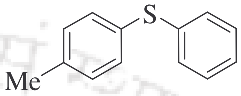
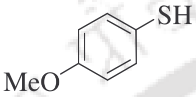
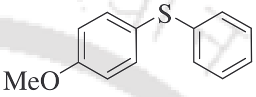
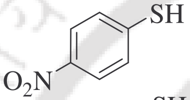
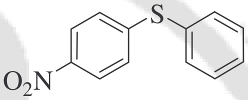
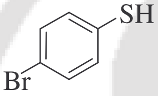
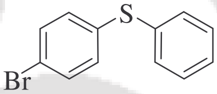
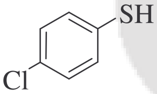
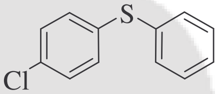
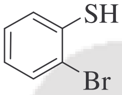
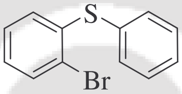
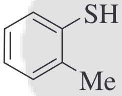
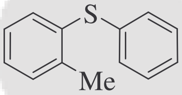
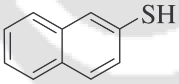
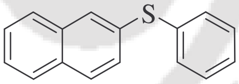
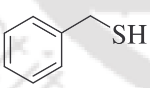
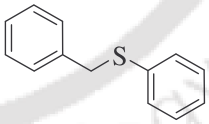
Entry	Aryl Halide	Yield (%)[a]
1	Iodobenzene	95
2	Bromobenzene	37[b]
3	Chlorobenzene	5[b]

[a] CuO nanoparticle (1.26 mol%), thiophenol (2 mmol), aryl halide (2.2 mmol) and KOH (3 mmol) were stirred for 10 h at 80 °C in DMSO (2 ml).

[b] Catalyst (5 mol%) used.

Table 4. The Cross-Coupling of Aryl Thiols with Iodobenzene



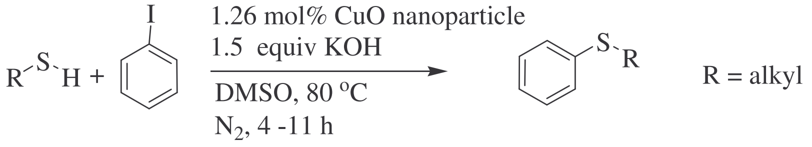
Entry	Aryl Thiol	Time (h)	Product	Yield (%)[a]
1		10		95
2		9		96
3		9.5		99
4		15		88
5		10		95
6		10		92
7		9		90
8		12		90
9		10		92
10		11		98

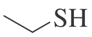
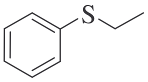
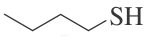
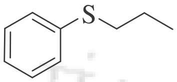
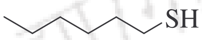
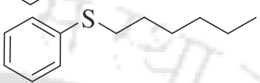
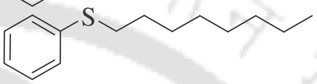
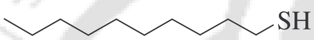
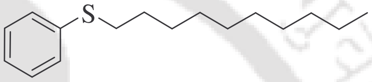
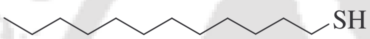
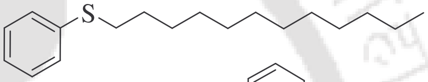
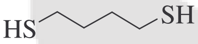
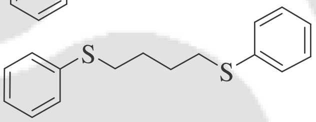
[a] CuO nanoparticle (1.26 mol%), thiol (2 mmol), iodobenzene (2.2 mmol) and KOH (3 mmol) were stirred at 80 °C in DMSO (2 mL).

the solvents studied, DMSO, DMF, 2-propanol, 1,4-dioxane and toluene, the former was found to be the choice for this reaction. Aryl iodides exhibited greater reactivity compared to aryl bromide and –chloride (Table 3).

Next, the coupling of aryl thiols with iodobenzene was studied (Table 4). Thiophenol having 2-bromo, 2-methyl, 4-bromo-, 4-chloro, 4-methyl-, 4-methoxy- and 4-nitro substituents underwent reaction to afford the corresponding cross-coupled product in high

Table 5. The Cross-Coupling of Alkyl Thiols with Iodobenzene

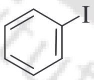
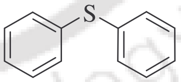
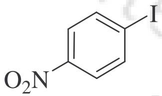
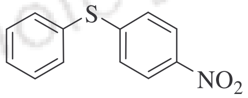
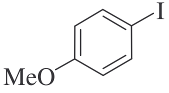
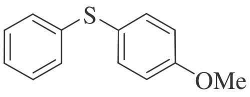


Entry	Alkyl Thiol	Time (h)	Product	Yield (%)[a]
1		4		95
2		6		96
3		7		91
4		7.5		90
5		8		89
6		11		85
7		5		90[b]

[a] CuO nanoparticle (1.26 mol%), alkyl thiol (2 mmol), iodobenzene (2.2 mmol) and KOH (3 mmol) were stirred at 80 °C in DMSO (2 mL) under N_2 atmosphere.

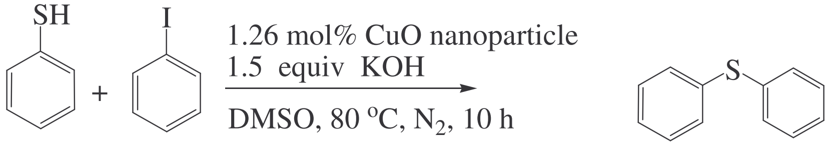
[b] Iodobenzene (4.4 mmol) and KOH (6 mmol) used.

Table 6. Reaction of Thiophenol with Substituted Aryl Iodides

Entry	Aryl Iodide	Time	Product	Yield (%)[a]
1		5		71
2		5		83
3		5		14

[a] CuO nanoparticle (1.26 mol%), thiophenol (2 mmol), aryl iodide (2.2 mmol) and KOH (3 mmol) were stirred at 80 °C in DMSO (2 mL) under N_2 atmosphere.

Table 7. Recyclability of CuO Nanoparticles



Run	Recoverability (%) of CuO nanoparticle	Diphenylsulfide (Yield, %)[a]
1	96	95
2[b]	93	89
3[b]	88	81

[a]CuO nanoparticle (1.26 mol%), thiophenol (2 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred at 80 °C in DMSO (2 mL) under nitrogen atmosphere.

[b]The recovered CuO nanoparticle used.

yields (Table 4). Thiophenol with electron donating group showed greater reactivity compared to that bearing electron withdrawing group. Similar results observed with 2-naphthyl thiol affording the *C-S* cross-coupled product in high yield. These reaction conditions were also suitable for the cross-coupling of alkyl thiols with iodobenzene (Table 5). Ethyl, butyl, hexyl, octyl and dodecyl thiol underwent reaction with iodobenzene to give the cross-coupled products in 85-96% yield. In the case of butane-1,4-dithiol, both the SH groups cross-coupled with iodobenzene with 90% yield.

Finally, the reaction of aryl iodides having electron withdrawing and -donating groups was studied (Table 6). 4-Nitro-1-iodobenzene underwent reaction with thiophenol in 83% yield. Under these conditions, iodobenzene was cross-coupled with thiophenol in 71% yield. While 4-methoxy-1-iodobenzene required longer reaction time to provide the desired cross-coupled product in 14% yield. These results clearly reveal that the reaction takes place via oxidative addition followed by reductive elimination process as described in chapter I of the thesis.

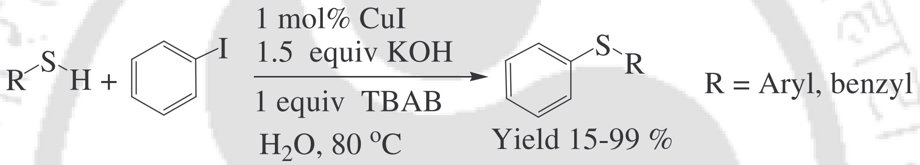
Recyclability of CuO Nanoparticles

The reaction is a heterogeneous process and the CuO nanoparticle can be recycled without loss of activity (Table 7). After completion the reaction of thiophenol with iodobenzene, the reaction mixture was treated with water and ethyl acetate. The aqueous layer after extraction with ethyl acetate, centrifuged and the CuO nanoparticle was recovered. It was reused for the fresh reaction of thiophenol with iodobenzene and the reaction occurred to afford the desired diphenyl sulfide. This process was repeated up to three runs and the cross-coupled product obtained in >81% yield.

In summary, the *C-S* cross-coupling of aryl and alkyl thiol with aryl iodides is accomplished using CuO nanoparticle under moderate temperature. The reactions are efficient affording the cross-coupled products with low concentration of the catalyst in high yields.

2.2.2 C-S Cross-Coupling Using CuI/TBAB in Water

The use of water as a solvent for organic reactions has been intensive in recent years.[9] Because water is cheap, nontoxic, safe and environmentally benign compared to organic solvents. This section focuses on *C-S* cross-coupling of aryl and benzyl thiols with aryl halides employing CuI in the presence of TBAB in water (Scheme 13).[10]



Scheme 13

First, the reaction of thiophenol was studied with iodobenzene as model substrate to optimize the reaction conditions. As anticipated the reaction occurred to afford the desired *C-S* cross-coupled product in 98% yield when thiol was stirred in the presence of 1 mol% CuI, 1.5 equiv KOH, 1 equiv TBAB and 1.1 equiv iodobenzene at 80 °C in water (Table 8).

Table 8. Cross-Coupling of Thiophenol with Iodobenzene with Different Copper Sources

Entry	Catalyst	Yield (%)[a]
1	$CuCl_2 \cdot 2H_2O$	90
2	$CuSO_4 \cdot 5H_2O$	76
3	$Cu(OAc)_2 \cdot 1H_2O$	88
4	CuO nanoparticle	72
5	$Cu(NO_3)_2 \cdot 3H_2O$	85
6	CuI	98

[a]Catalyst (1 mol%), thiophenol (2 mmol), iodobenzene (2.2 mmol), KOH (3 mmol) and TBAB (2 mmol) were stirred for 10 h at 80 °C in water (2 mL).

The reaction with CuI was superior to that used $CuCl_2 \cdot 2H_2O$, $CuSO_4 \cdot 5H_2O$, $Cu(OAc)_2 \cdot 1H_2O$ and $Cu(NO_3)_2 \cdot 3H_2O$ as catalysts. The presence of TBAB is essential in its absence no reaction was observed. The reaction using KOH was superior to that used Cs_2CO_3, K_2CO_3, pyridine and diisopropylamine as a base (Table 9). Aryl iodide was more reactive compared to aryl bromide and -chloride (Table 10).

Table 9. Reaction of Thiophenol with Iodobenzene: The Effect of Base and Temperature

Entry	Base	Temp.(°C)	Time (h)	Yield (%)[a]
1	KOH	RT	12	0
2	K_2CO_3	80	10	75
3	Cs_2CO_3	80	10	88
4	DIPA	80	8	65
5	Pyridine	80	8	75

[a] CuI (1 mol%), thiophenol (2 mmol), iodobenzene (2.2 mmol), base (3 mmol) and TBAB (2 mmol) were stirred at 80 °C in water (2 mL).

Table 10. Cross-Coupling of Thiophenol with Aryl Halides

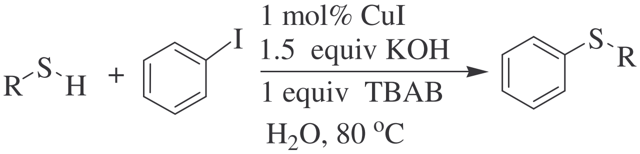
Entry	Aryl halide	Time (h)	Yield (%)[a]
1	Iodobenzene	10	98
2	Bromobenzene	12	52[b]
3	Chlorobenzene	12	32[b]

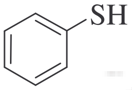
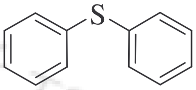
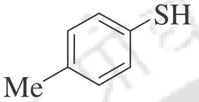
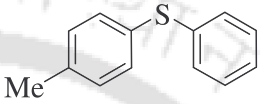
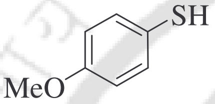
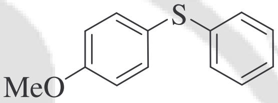
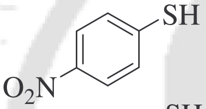
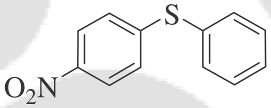
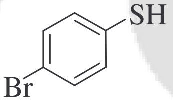
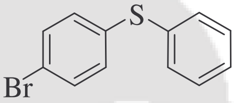
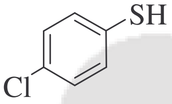
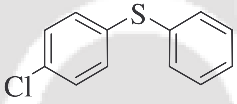
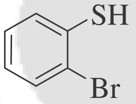
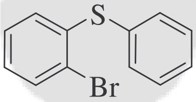
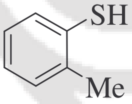
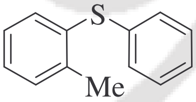
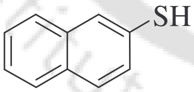
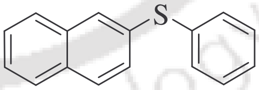
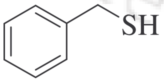
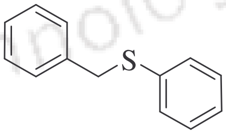
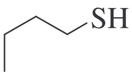
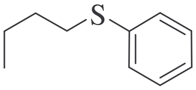
[a] CuI (1 mol%), thiophenol (2 mmol), aryl halide (2.2 mmol), KOH (3 mmol) and TBAB (2 mmol) were stirred at 80 °C in water (2 mL).

[d] Catalyst (5 mol%) used.

Next, the reactions of other thiols were examined with iodobenzene (Table 11). Thiophenol having 2-methyl-, 4-methyl-, 4-nitro-, 2-bromo-, 4-bromo-, 4-chloro-, and 4-methoxy substituents underwent reaction to give the desired products in 91–99% yield.

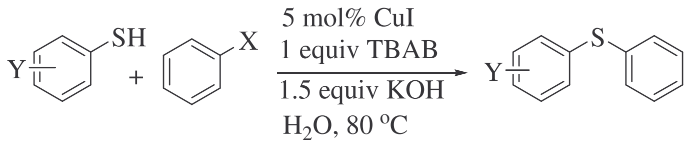
Table 11. CuI Catalyzed Cross-Coupling of Thiols with Iodobenzene in Water



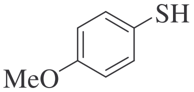
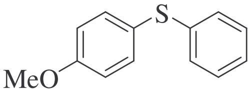
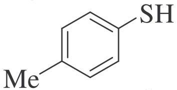
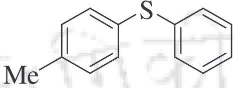
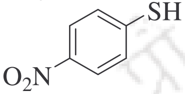
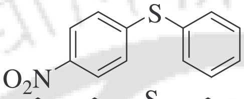
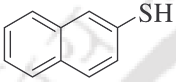
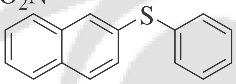
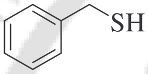
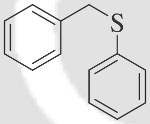
Entry	Thiol	Time (h)	Product	Yield (%)[a]
1		10		98
2		9		99
3		9.5		99
4		15		91
5		11		95
6		9		94
7		10		96
8		9		98
9		10		99
10		11		91
11		15		15

[a] CuI (1 mol%), thiol (2 mmol), iodobenzene (2.2 mmol), TBAB (2 mmol) and KOH (3 mmol) were stirred at 80 °C in water (2 mL).

Table 12. Reaction of Thiols with Chloro- and Bromobenzene

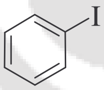
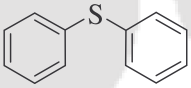
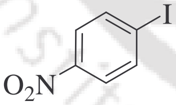
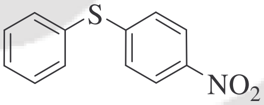
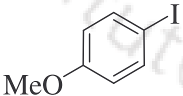
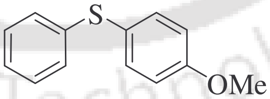
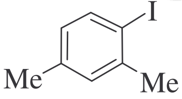
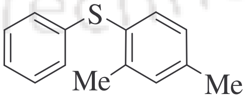


X = Cl, Br

Entry	Thiol	Product	X = Br		X = Cl	
			Time (h)	Yield (%)[a]	Time (h)	Yield (%)[a]
1			15	60	15	45
2			14	50	14	39
3			15	41	15	30
4			18	48	18	30
5			19	32	19	21

[a] CuI (5 mol%), thiol (2 mmol), aryl halide (2.2 mmol), KOH (3 mmol) and TBAB (2 mmol) were stirred at 80 °C in water.

Table 13. Reaction of Thiophenol with Substituted Aryl Iodides

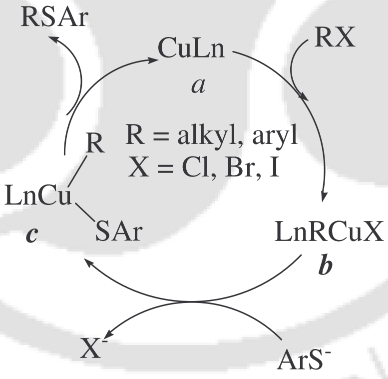
Entry	Aryl Iodide	Product	Time (h)	Yield (%)[a]
1			8	76
2			6	95
3			12	75
4			12	85

[a] CuI (1 mol%), thiophenol (2 mmol), aryl iodide (2.2 mmol), KOH (3 mmmol) and DMSO (1 mL) / TBAB (2 mmol) and H_2O (2 mL) were stirred for appropriate time at 80 °C.

Similar results were observed with 2-naphthalenethiol and phenylmethanethiol. While 1-butanethiol was less reactive affording the *C–S* cross-coupled product in 15% yield. Thiophenol containing electron donating group was more reactive compared to that having electron withdrawing group. These reaction conditions are also suitable for the cross-coupling of thiols with chloro- and bromobenzene (Table 12). For examples, 4-methoxy-, 4-methyl-, and 4-nitrobenzenethiol, 2-naphthalenethiol and phenylmethanethiol underwent cross-coupling with chloro- and bromobenzene in moderate yields.

2.2.2.1 Mechanism

Finally, the reactions of thiophenol with aryl iodides that have electron-donating and -withdrawing substituents were investigated (Table 13). The reaction with 1-iodo-4-nitrobenzene afforded the product in 95% yield, while the reactions of 1-iodo-4-methoxybenzene and 1-iodo-2,4-dimethylbenzene required 12 h to provide the cross-coupling products in 75% and 85% yield, respectively. These results suggest that the reaction occurs by oxidative addition followed by reductive elimination processes (Scheme 14). The oxidative addition of the aryl halides with catalyst ***a*** can give intermediate ***b***, which can undergo reaction with thiol to afford intermediate ***c***. Intermediate ***c*** can provide the *C*-*S* cross-coupling product by reductive elimination, where TBAB presumably acts as the phase-transfer catalyst, solubilizing the organic substrates in water.



Scheme 14. Proposed Catalytic Cycle for CuI-TBAB System

Recyclability of CuO Nanoparticles

A mixture of iodobenzene (2.2 mmol, 448 mg), thiophenol (2 mmol, 220 mg), CuO nanoparticle (1.26 mol%, 2 mg) and KOH (3 mmol, 168 mg) was stirred at 80 ^{o}C under N_2 in DMSO (2 mL). The reaction mixture was treated with ethyl acetate (10 mL) and water (3 mL). The aqueous layer was separated and centrifuged with 10,000 rpm for an hour to provide the CuO nanoparticles. It was, after drying under vacuum, reused for the fresh reaction of thiophenol with iodobenzene for three recycles and no loss of activity observed.

In summary, the *C*-*S* cross-coupling of thiols with aryl halides is accomplished using CuI in the presence of TBAB in water. Aryl and benzyl thiols are more reactive compared to alkyl thiols affording the *C*-*S* cross-coupled products in high yields.

Experimental Section

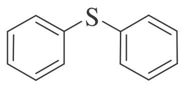
General. Thiols and CuI (98%) are purchased from Aldrich.

General Procedure for CuO Nanoparticle Catalyzed Reactions

A mixture of aryl halide (2.2 mmol), thiol (2 mmol), CuO nanoparticles (1.26 mol%) and KOH (3 mmol) was stirred at 80 ^{o}C under N_2 in DMSO (2 mL). The progress of the reaction was monitored by TLC. After completion, the reaction mixture was treated with water (3 mL) and ethyl acetate (10 mL). The organic and aqueous layers were separated, and the aqueous layer was extracted with ethyl acetate (5 mL). The combined organic solutions were washed with brine (1 x 5 mL) and water (1 x 5 mL). Drying (Na_2SO_4) and evaporation of the solvent provided residue that was passed through a short pad of celite to give analytically pure *C*-*S* cross-coupled product.

General Procedure for CuI Catalyzed Reactions in Water

To a stirred solution of thiol (2 mmol), aryl halide (2.2 mmol), TBAB (2 mmol) and KOH (3 mmol) in water (2 mL), CuI (1-5 mol %) was added. The solution was heated at 80 ^{o}C under air for the appropriate time. The progress of the reaction was monitored by TLC. The reaction mixture was then cooled to room temperature and treated with diethyl ether (10 mL). The aqueous layer was separated and extracted with diethyl ether (3 x 5 mL). The combined organic solution was successively washed with brine (3 x 5 mL) and water (1 x 5 mL). Drying (Na_2SO_4) and evaporation of the solvent under reduced pressure provided a residue that was passed through a short pad of silica gel by using ethyl acetate and hexane as eluent to afford analytically pure *C*-*S* cross-coupled product.



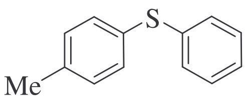
Diphenyl sulfide. Thiophenol (2 mmol, 220 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction conditions described in the general procedure for 10 h to afford diphenyl sulfide as a colorless oil in 98% (364 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.35-7.22 (m, 10H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 136.21, 131.46, 129.60, 127.45.

IR (neat): ν 3072, 3058, 3034, 3003, 1580, 1475, 1439, 1023, 737, 689 cm^{-1}.

Anal Calcd for $C_{12}H_{10}S$: C, 77.37; H, 5.41; S, 17.21. Found: C, 77.38; H, 5.45; S, 17.24.



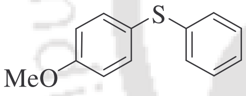
4-Tolyl phenyl sulfide. 4-Methylthiophenol (2 mmol, 248 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction condition described in the general procedure for 9 h to afford 4-tolylphenyl sulfide as a colorless oil in 99% (396 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.30-7.25 (m, 6H), 7.20-7.12 (m, 3H), 2.31(s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 137.80, 137.31, 132.48, 131.43, 130.26, 129.94, 129.24, 126.59, 21.34.

IR (neat): ν 3050, 2930, 1590, 1490, 1480, 1440, 1090, 1020, 810, 740, 690 cm^{-1}.

Anal Calcd for $C_{13}H_{12}S$: C, 77.95; H, 6.04; S, 16.01. Found: C, 77.94; H, 6.05; S, 16.05.



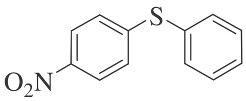
Phenyl sulfanyl anisole. 4-Methoxythiophenol (2 mmol, 280 mg), iodobenzene (2.2 mmol, 453 mg), KOH (2.5 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 9 h to afford *p*-anisylphenyl sulfide as a colorless oil in 99% (427 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.38-7.37 (dd, 2H, J = 8.8, 2.8 Hz), 7.23-7.12 (m, 5H), 6.88-6.85 (dd, 2H, J = 8.8, 2.4 Hz), 3.78 (s, 3H).

^{13}C NMR($CDCl_3$, 100 MHz) δ 159.99, 138.79, 135.56, 129.10,128.32, 125.91, 124.41, 115.15, 55.52.

IR (neat): ν 3085, 3042, 2942, 2919, 2802, 690 cm^{-1}.

Anal Calcd for $C_{13}H_{12}SO$: C, 72.19; H, 5.59; S, 14.82. Found: C, 72.20; H, 5.60; S, 14.85.



4-Nitrophenyl phenyl sulfide. 4-Nitrothiophenol (2 mmol, 312 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction condition described in the general procedure for 15 h to afford 4-nitrophenyl phenyl sulfide as yellow solid in 91% (420 mg) yield.

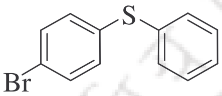
Mp: 54 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.06 (dd, *J* = 8.8, 2.0 Hz, 2H), 7.55-7.53 (m, 2H), 7.47-7.45 (m, 3H), 7.16 (d, *J* = 8.4 Hz, 2H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 148.74, 134.97, 130.59, 130.24, 129.89, 126.84, 124.24.

IR (KBr): ν 3062, 1575, 1512, 1475, 1440, 1334, 1082, 1024, 851, 741,691, 504. cm^{-1}.

Anal Calcd for $C_{12}H_9SNO_3$: C, 62.32; H, 3.92; N 6.06; S, 13.86. Found: C, 62.34; H, 3.93; N 6.09; S, 13.88.



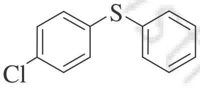
4-Bromophenyl phenyl sulfide. 4-Bromothiophenol (2 mmol, 376 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 10 h to afford 4-bromophenyl phenyl sulfide as colorless oil in 95% (503 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.40 (dd, *J* = 6.8, 4.8 Hz, 2H), 7.36 -7.25 (m, 5H), 7.18 -7.16 (dd, *J* = 6.8, 4.8 Hz, 2H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 135.99, 132.74, 132.59, 132.06, 129.89, 128.08.

IR (neat): ν 3060, 1591, 1483, 1096, 1014, 824, 742, 693 cm^{-1}.

Anal Calcd for $C_{12}H_9SBr$: C, 54.35; H, 3.42; S, 12.09. Found: C, 54.40; H, 3.43; S, 12.13.



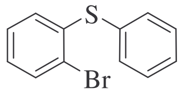
4-Chlorophenyl phenyl sulfide. 4-Chlorothiophenol (2 mmol, 288 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction condition described in the general procedure for 9 h to afford 4-chlorophenyl phenyl sulfide as colorless oil in 94% (413 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.27 -7.13 (m, 2H), 7.36 -7.25 (m, 5H). 7.18 -7.16 (dd, 2H, *J* = 6.8, 4.8 Hz).

^{13}C NMR ($CDCl_3$, 100 MHz) δ137.66, 137.17, 134.82, 132.20, 131.51, 130.44, 129.54, 129.52, 127.64.

IR (neat): ν 3060, 1590, 1480, 1090, 1010,820, 740, 690 cm^{-1}.

Anal Calcd for $C_{12}H_9SCl$: C, 65.30; H, 4.11; S, 14.53. Found: C, 65.31; H, 4.12, S; 14.56.



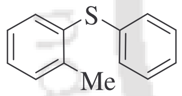
2-Bromophenyl phenyl sulfide. 2-Bromothiophenol (2 mmol, 376 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction condition described in the general procedure for 10 h to afford 2-bromophenyl phenyl sulfide as colorless oil in 96% (508 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.57 -7.55 (d, *J* = 8 Hz, 2H), 7.49 -7.44 (m, 2H). 7.41-7.36 (m, 2H), 7.24 -7.23 (m, 1H), 7.16 -7.12 (m, 1H), 7.05 -7.01 (m, 1H), 6.92-6.90 (d, *J* = 8 Hz,1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 133.74, 133.23, 129.91, 129.86, 128.95, 128.70, 128.02, 127.89, 127.44.

IR (neat): ν 3390, 2921, 1636, 1440, 1258, 1102, 1048, 1018, 795, 744 cm^{-1}.

Anal Calcd for $C_{12}H_9SBr$: C, 54.35; H, 3.42; S, 12.10. Found: C, 54.40; H, 3.43; S, 12.13.



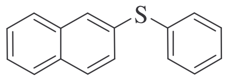
2-Tolyl phenyl sulfide. 2-Methylthiophenol (2 mmol, 248 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction condition described in the general procedure for 9 h to afford 2-tolyl phenyl sulfide as colorless oil in 98% (392 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.21-7.03 (m, 9H), 2.29 (s, 3H).

^{13}CNMR ($CDCl_3$, 100 MHz) δ 140.15, 136.30, 133.92, 133.16, 130.79, 129.82, 129.32, 128.09, 126.91, 126.54, 20.80.

IR (neat): ν 3050, 3022, 2932, 2857, 741, 690 cm^{-1}.

Anal Calcd for $C_{13}H_{12}S$: C, 77.95; H, 6.04; S, 16.01. Found: C, 77.93; H, 6.05; S, 16.05.



2-Naphthyl phenyl sulfide. 2-Naphthalenethiol (2 mmol, 320 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuI (1 mol%, 4 mg), TBAB (2 mmol, 644 mg) and H_2O (2 mL) were subjected to the reaction condition described in the general procedure for 10 h to afford 2-naphthyl phenyl sulfide as colorless solid in 99% (467 mg) yield.

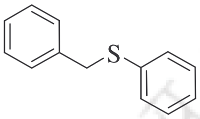
Mp: 49 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.83-7.76 (m, 2H), 7.74-7.70 (m, 2H), 7.48 -7.44 (m, 2H), 7.41-7.36 (m, 2H), 7.32 -7.23 (m, 4H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 131.14, 130.08, 129.44, 129.07, 128.95, 127.94, 127.62, 127.27, 126.80, 126.42.

IR (KBr): ν 3054, 1582, 1503, 1477, 1438, 1380, 1024, 971, 798, 771, 739, 689 cm^{-1}.

Anal Calcd for $C_{16}H_{12}S$: C, 81.31; H, 5.12; S, 13.57. Found: C, 81.32; H, 5.14; S, 13.60.



Benzyl phenyl sulfide. Benzyl mercaptan (2 mmol, 248 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 11 h to afford benzyl phenyl sulfide as colorless solid in 98% (392 mg) yield.

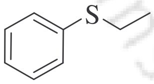
Mp: 40 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.31 -7.23 (m, 10H), 4.12 (s, 2H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 130.08, 129.05, 128.70, 127.38, 126.56, 39.28.

IR (KBr): ν 3072, 3058, 3034, 3003, 1580, 1475, 1439, 1023, 737, 689 cm^{-1}.

Anal Calcd for $C_{13}H_{12}S$: C, 77.95; H, 6.04; S, 16.01. Found: C, 77.94; H, 6.06; S, 16.02.



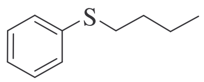
***n*-Ethyl phenyl sulfide.** Ethanethiol (2 mmol, 124 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 4 h to afford *n*-ethyl phenyl sulfide as a colorless oil in 95% (262 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.33 -7.25 (m, 4H), 7.17-7.15 (m, 1H), 2.94 (m, 2H). 1.30 (*t*, J = 7.2 Hz, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 136.79, 129.16, 129.00, 125.92, 27.78, 14.54.

IR (neat): ν 3396, 2927, 2867, 1634, 1400, 1392, 1263, 1104, 806, 790 cm^{-1}.

Anal Calcd for $C_8H_{10}S$: C, 69.51; H, 7.29; S, 23.20. Found: C, 69.53; H, 7.28; S, 23.19.



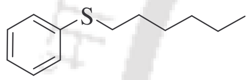
***n*-Butyl phenyl sulfide.** Butanethiol (2 mmol, 180 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 6 h to afford *n*-butyl phenyl sulfide as a colorless oil in 96% (318 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.32 -7.24 (m, 4H), 7.16-7.14 (m, 1H), 2.88 (*t*, *J* = 7.6 Hz, 2H). 1.64-1.59 (m, 2H), 1.47-1.41(m, 2H) , 0.90 (*t*, *J* =2.7 Hz, 3H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 137.55, 130.32, 128.90,125.67, 33.28, 31.31, 22.08, 13.78.

IR (neat): ν 3252, 2923, 2246, 1635, 1577, 1473, 1434, 1262, 1095, 1070, 1021, 738, 686 cm^{-1}.

Anal Calcd for $C_{10}H_{14}S$: C, 72.23; H, 8.49; S, 19.28. Found: C, 72.24; H, 8.51; S, 19.30.



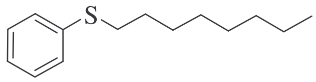
***n*-Hexy phenyl sulfide.** Hexylthiol (2 mmol, 336 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 7 h to afford *n*-hexyl phenyl sulfide as a colorless oil in 91% (353 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.31-7.24 (m, 4H), 7.14-7.13 (m, 1H), 2.89 (*t*, *J* = 7.6 Hz, 2H), 1.65-1.59 (m, 2H), 1.42-1.39 (m, 4H) , 1.37-1.25 (m, 2H) , 0.85 (*t*, *J* =6.8 Hz, 3H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 137.24, 128.93, 125.72, 33.68, 31.53, 29.26, 28.69, 22.70, 14.19.

IR (neat): ν 3373, 3075, 3058, 3033, 3002, 1582, 1476, 1440, 1319, 1023, 737, 683 cm^{-1}.

Anal Calcd for $C_{12}H_{18}S$: C, 75.16; H, 9.34; S, 16.50. Found: C, 74.18; H, 9.34; S, 16.48.



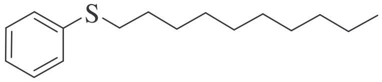
***n*-Octyl phenyl sulfide.** Octylthiol (2 mmol, 292 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 7.5 h to afford *n*-octyl phenyl sulfide as a colorless oil in 90% (399 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.32 -7.25 (m, 4H), 7.17-7.15 (m, 1H), 2.91 (*t*, *J* = 7.6 Hz, 2H), 1.66-1.56 (m, 2H), 1.43-1.26 (m, 10H), 0.87 (*t*, *J* =6.4 Hz, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 137.63, 130.39, 128.96, 125.74, 33.69, 31.98, 29.35, 29.31, 29.03, 22.83, 14.29.

IR (neat): ν 3030, 3012, 2937, 2930, 2919, 1648, 1467, 1440, 1415, 1319, 1141, 1020, 949, 743, 710, 683, 598 cm^{-1}.

Anal Calcd for $C_{14}H_{22}S$: C, 75.61; H, 9.97; S, 14.42. Found: C, 75.66; H, 9.96; S, 14.43.



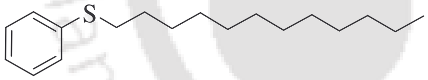
***n*-Decyl phenyl sulfide.** Decylthiol (2 mmol, 348 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 8 h to afford *n*-decyl phenyl sulfide as a colorless oil in 89% (445 mg) yield.

^{1}HNMR ($CDCl_3$, 400 MHz) δ 7.32 -7.59 (m, 4H), 7.17-7.15 (m, 1H), 2.91 (*t*, *J* = 7.6 Hz, 2H), 1.66-1.60 (m, 4H), 1.42-1.37 (m, 12H), 0.88 (*t*, *J* = 6 Hz, 3H).

^{13}CNMR ($CDCl_3$, 100 MHz) δ 137.43, 129.01, 125.81, 33.76, 32.12, 29.84, 29.55, 29.37, 29.06, 22.90,14.33.

IR (neat): ν 3373, 3065, 2956, 1967, 1945, 1862, 1635, 1574, 1473, 1456, 1436, 1294, 1262, 1086, 1070, 1020, 798, 738, 598 cm^{-1}.

Anal Calcd for $C_{16}H_{26}S$: C, 76.73; H, 10.46; S, 12.80. Found: C, 76.75; H, 10.45; S, 12.83.



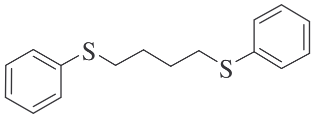
***n*-Dodecyl phenyl sulfide.** Dodecylthiol (2 mmol, 404 mg), iodobenzene (2.2 mmol, 453 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 11 h to afford *n*-dodecyl phenyl sulfide as colorless oil in 85% (472 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.33 -7.26 (m, 4H), 7.25-7.13 (m, 1H), 2.91 (*t*, *J* = 7.6 Hz, 2H), 1.66-1.56 (m, 4H), 1.43-1.25 (m, 16H), 0.88-0.86 (m, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ137.43, 129.01, 125.80, 33.76, 32.12, 29.83, 29.55, 29.45, 29.37, 29.05, 28.74, 26.62, 23.73, 22.90, 14.32.

IR (neat): ν 3358, 3283, 2921, 2851, 1602, 1451, 1438, 1260, 1091, 795, 735 cm^{-1}.

Anal Calcd for $C_{18}H_{30}S$: C, 77.63, H, 10.85, S, 11.51. Found: C, 77.64, H, 10.83; S, 11.53.



1,4-Diphenyl butyl sulfide. 1,4-Butanethiol (2 mmol, 244 mg), iodobenzene (4.4 mmol, 906 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 2 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 7.5 h to afford 1,4-diphenyl butyl sulfide as colorless solid in 90% (493 mg) yield.

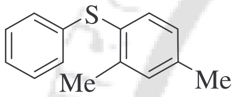
Mp: 84 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.29 -7.23 (m, 8H), 7.16 -7.14 (m, 2H), 2.90-2.87 (m, 4H), 1.76-1.73 (m, 4H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 137.63, 129.44, 129.10, 33.47, 28.32.

IR (KBr): ν 3339, 3310, 2917, 2879, 1632, 1445, 1393, 1100 cm^{-1}.

Anal Calcd for $C_{16}H_{18}S_2$: C, 70.02; H, 6.61; S, 23.37. Found: C, 70.06; H, 7.63; S, 23.40.



2,4-Dimethylphenyl phenyl sulfide. Thiophenol (2 mmol, 220 mg), 2,4-dimethylphenyl 1-iodobenzene (2.2 mmol, 510 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (1.26 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 12 h to afford 2,4-dimethylphenyl phenyl sulfide as a colorless liquid in 85% (364 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.22-7.20 (d, J = 8.0 Hz, 1H), 7.18-7.12 (m, 2H), 7.07 - 7.01 (m, 4H), 6.91-6.89 (d, J = 8.0 Hz, 1H) 2.25 (s, 6H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 141.05, 138.77, 134.84, 131.80, 129.18, 128.48, 127.78, 125.81, 21.30, 20.79.

IR (neat): ν 3050, 2930, 1590, 1490, 1480, 1440, 1090, 1020, 810, 740, 690 cm^{-1}.

Anal Calcd for $C_{14}H_{14}S$: C, 78.46; H, 6.58; S, 14.96. Found: C, 78.47; H, 6.59; S, 14.94.

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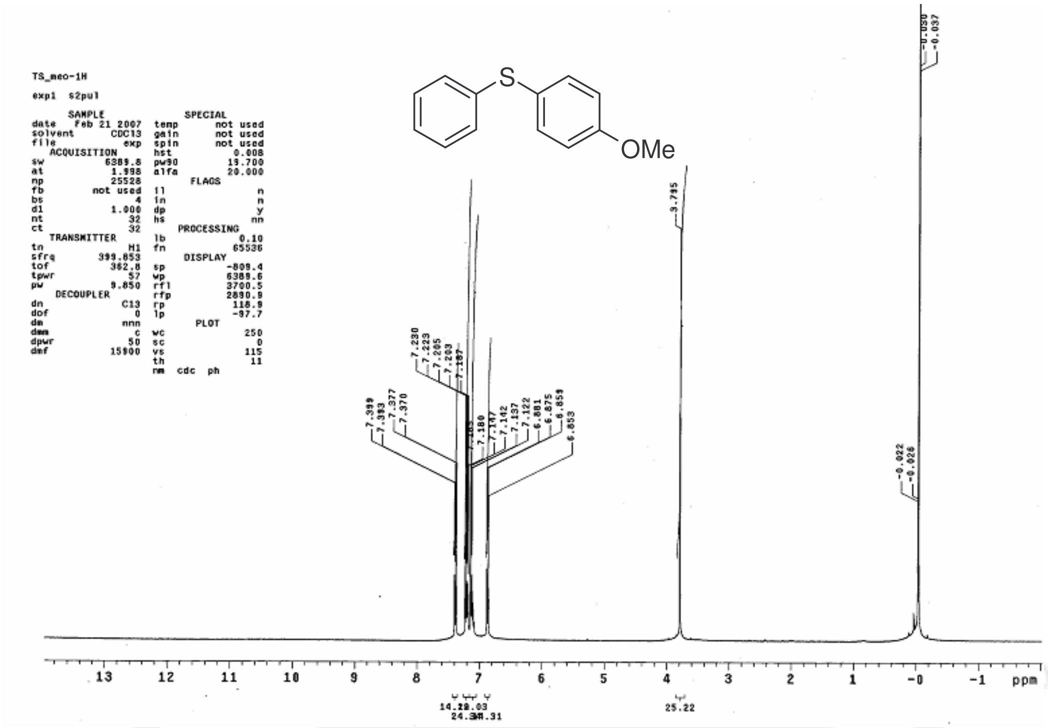

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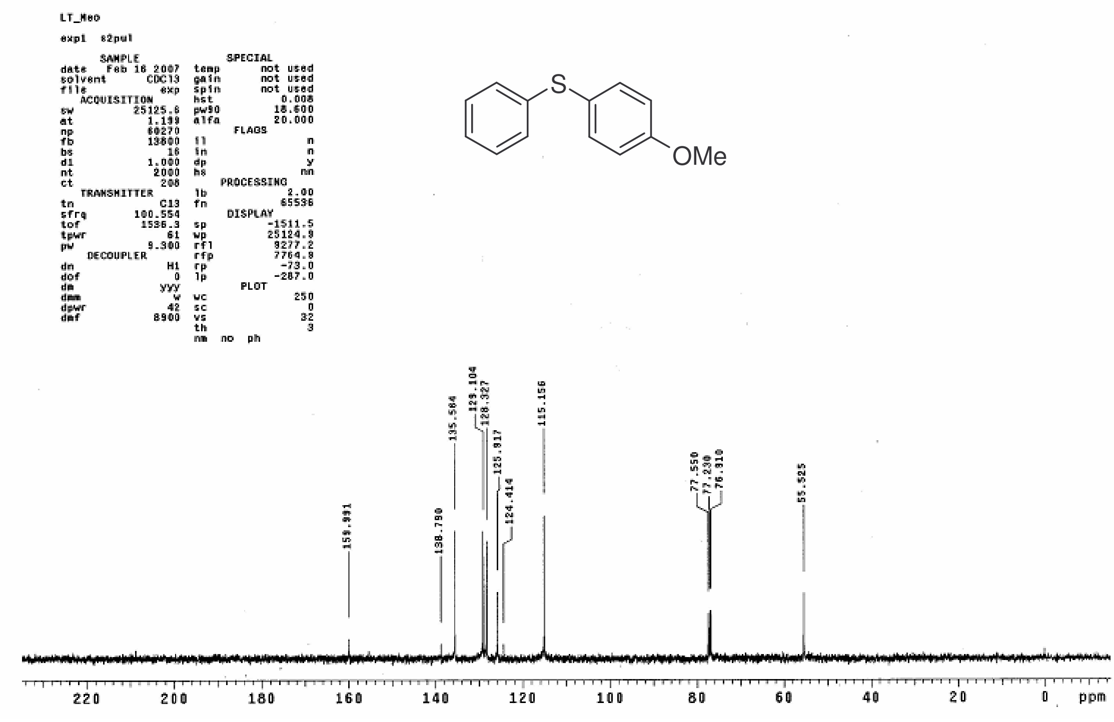

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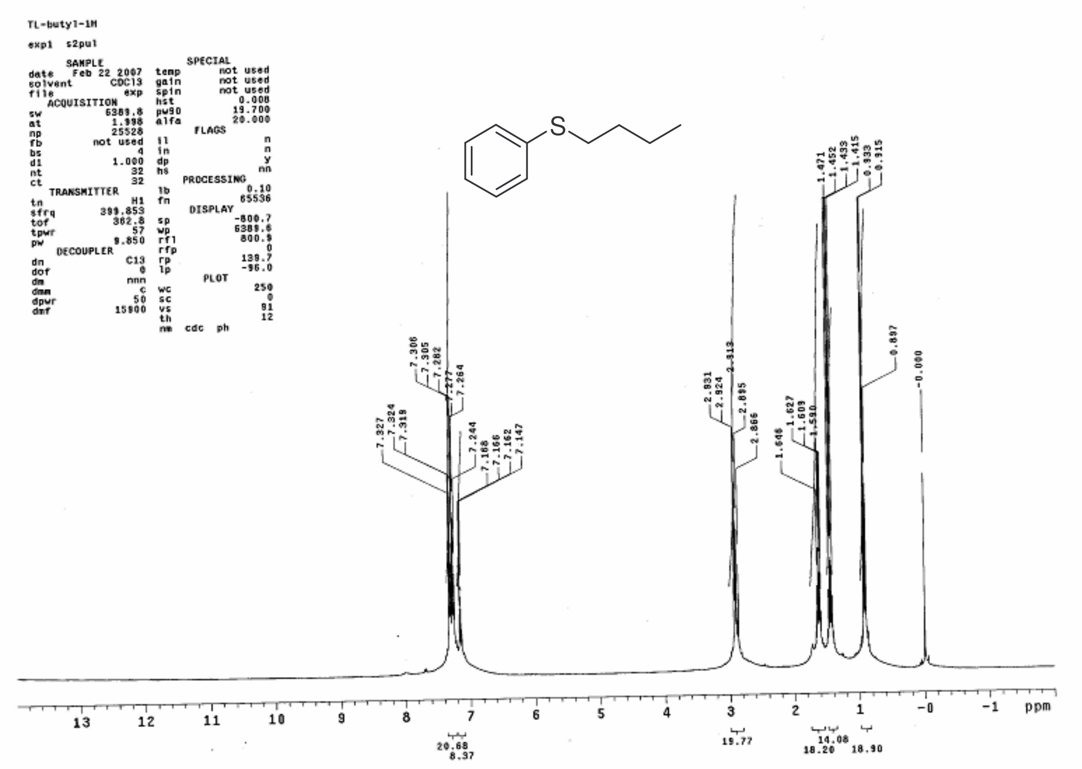
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7.147
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1.627
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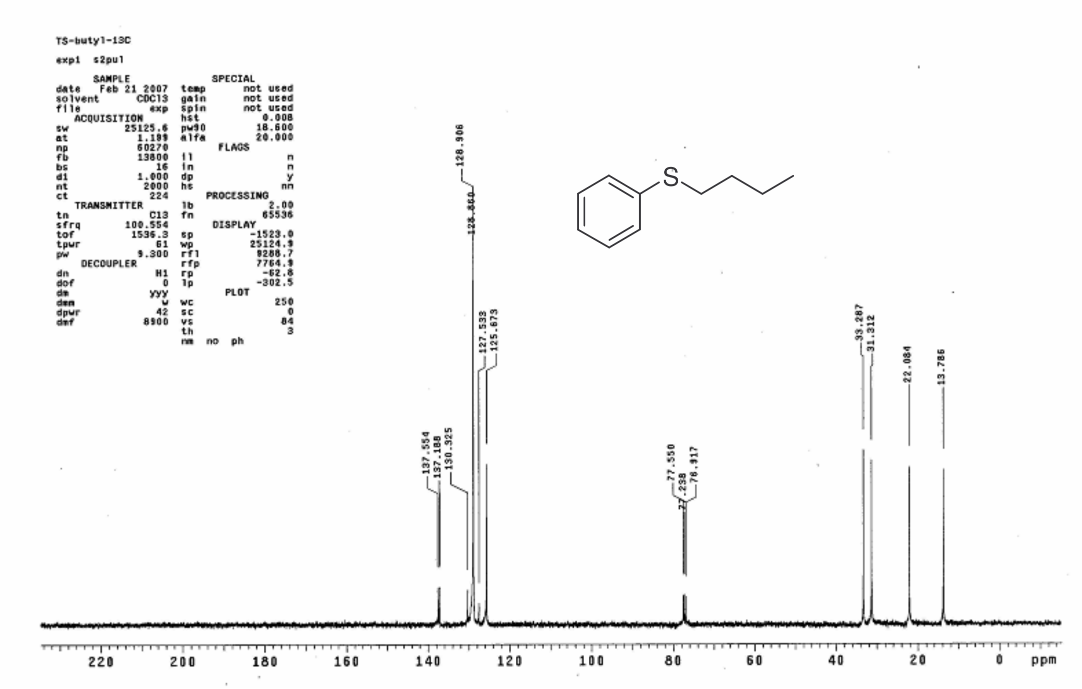
18.20
18.90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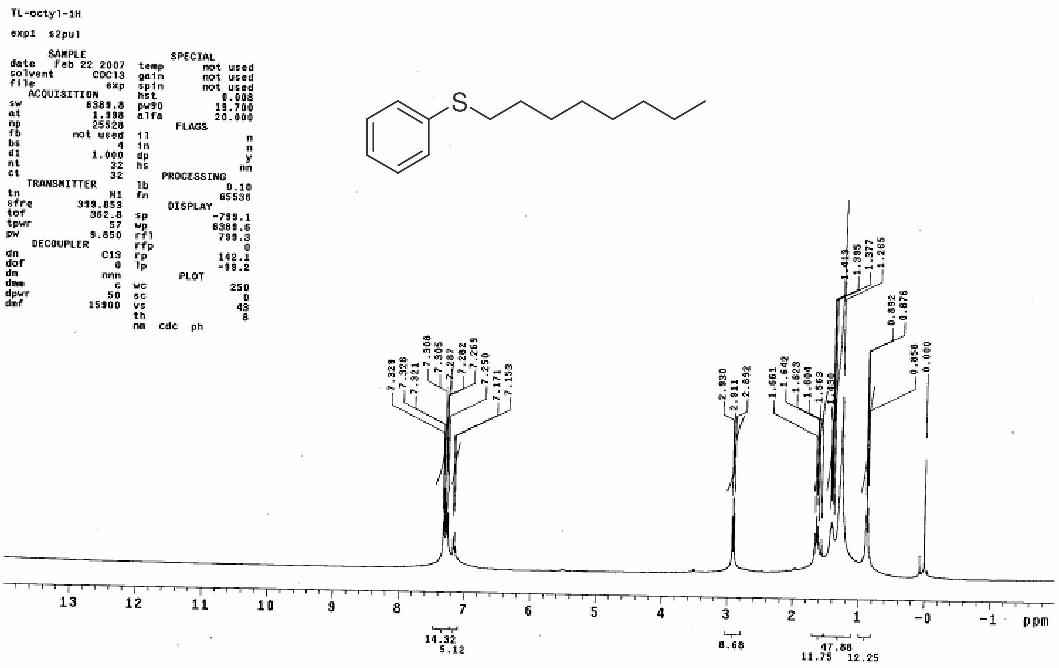

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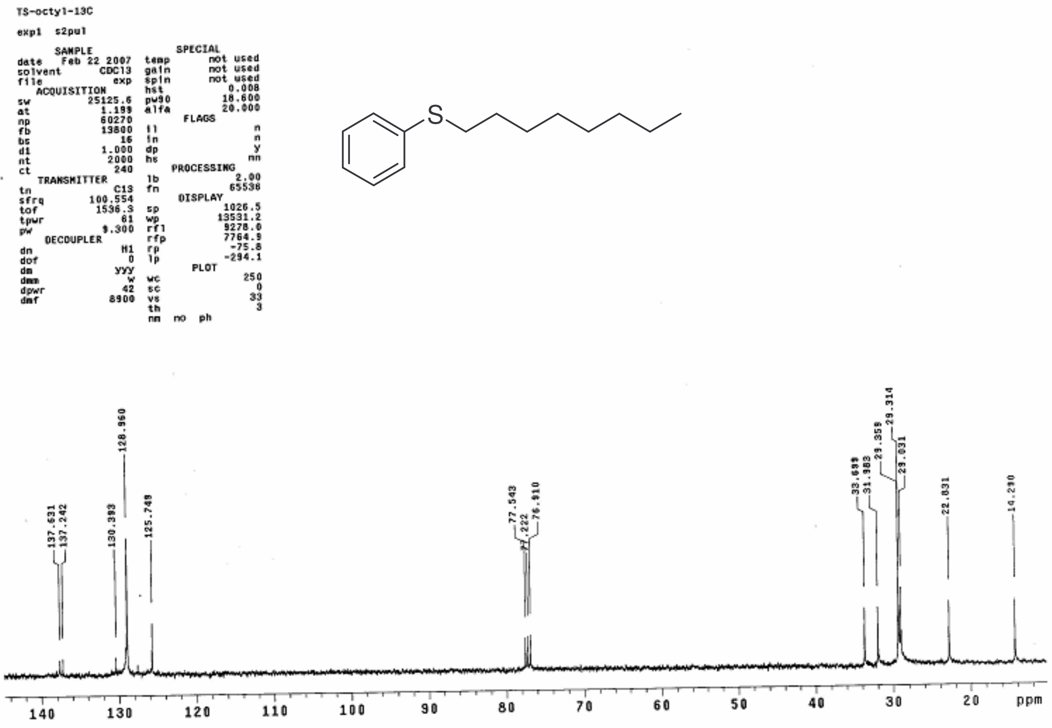

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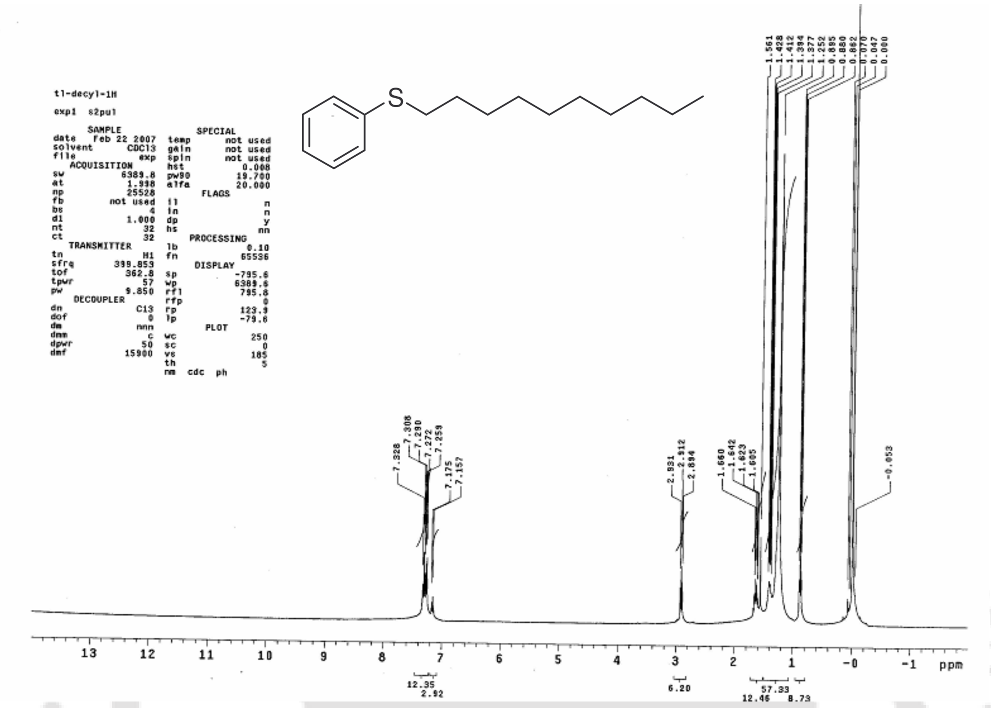

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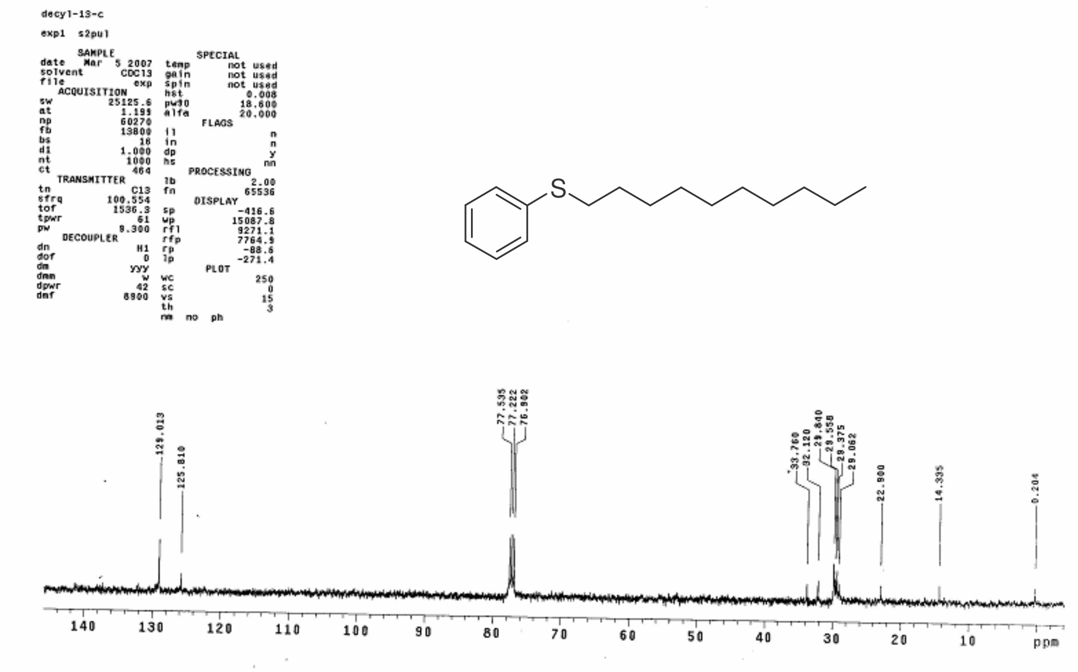

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                      th                  3
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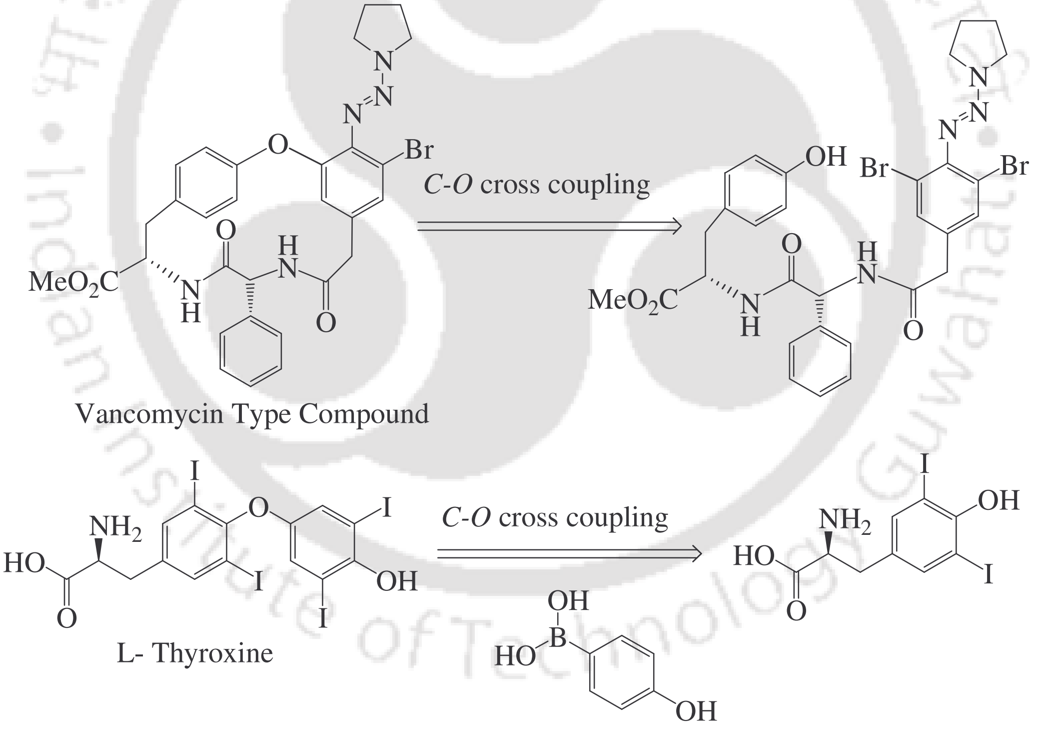
Chapter III

O-Arylation of Aryl Halides with Oxygen Nucleophiles

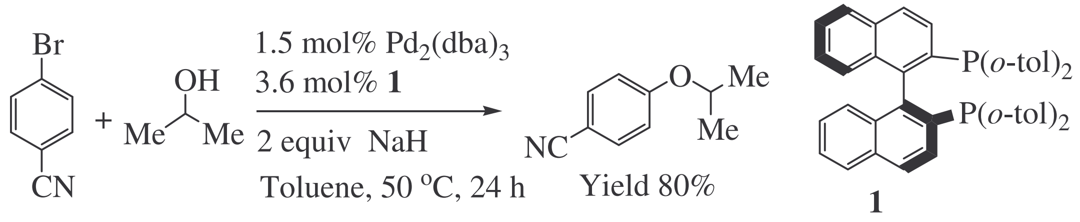
Aryl ethers are common structures in numerous pharmaceutically and agriculturally important compounds (Scheme 1).[1] Traditional methods for the preparation of these compounds include the Williamson ether synthesis,[2] direct nucleophilic substitution reactions[3] and Ullmann-type couplings of alkoxides with aryl halides.[4] Each of these reactions, however, typically requires either highly reactive aryl halide, an excess of the alkoxide or harsh conditions such as high temperature (125–300 °C) and stoichiometric or greater amount of copper reagent which, on scale-up, leads to problem of waste disposal.[5] To overcome these drawbacks, much attention has been focused in recent years to develop catalytic systems for *C-O* bond formation by cross-coupling reactions.



Scheme 1

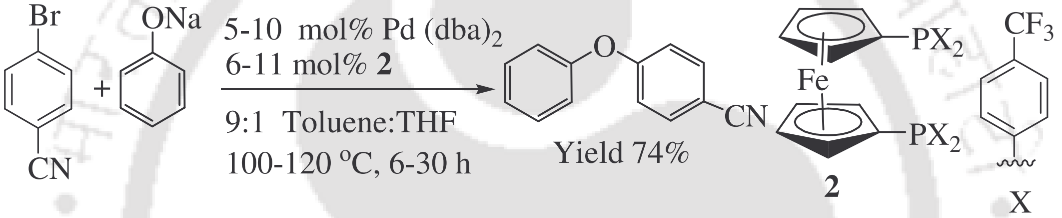
3.1.1 Palladium Catalysts

Palladium based catalysts are considerably studied for cross-coupling of aryl halides with hydroxy compounds.[6] The coupling of aliphatic alcohols with aryl bromide is studied by the combined use of $Pd_2(dba)_2$ and (*S*)-(-)-2,2`-bis(di-*p*-tolyl phosphino)-1,1`-binapthyl **1** in the presence of NaH in toluene (Scheme 2).[6a] Aryl bromides having electron with drawing groups undergo coupling effectively in high yields.



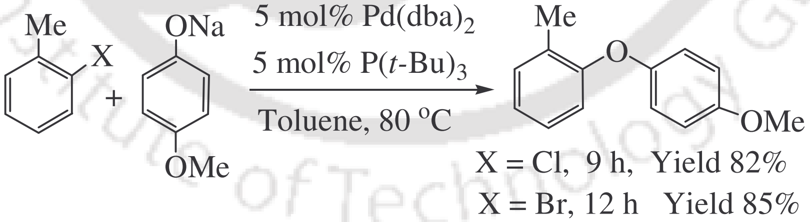
Scheme 2

Hartwig and Mann reported the coupling of aryl alkoxides with aryl bromides using $Pd(dba)_2$ and CF_3-dppf **2** [dppf =1,1'-bis (trifluoromethyl)phenyl phosphino ferrocene)] in a mixture of THF and toluene (Scheme 3).[6b] Series of aryl bromides bearing electron withdrawing groups are investigated with high yields.



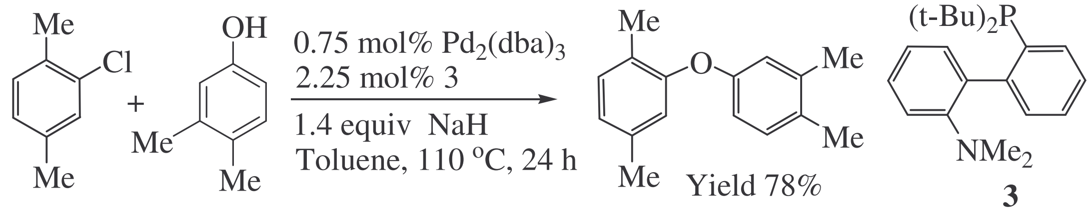
Scheme 3

These authors also further demonstrated the coupling of aryl alkoxide with aryl bromide using $Pd(dba)_2$-$P(t\text{-}Bu)_3$ in toluene (Scheme 4).[6c] Under these conditions aryl chlorides undergo reactions more efficiently compared to aryl bromides and –iodides at moderate temperature.



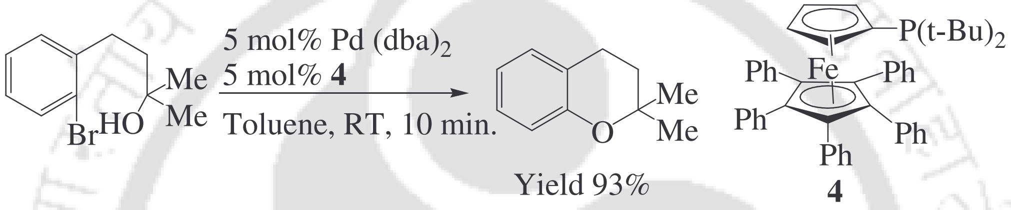
Scheme 4

Buchwald and co-workers showed the cross-coupling of phenols with aryl halides by the combined use of $Pd_2(dba)_3$ and electron rich and bulky aryl dialkyl phosphine **3** in the presence of NaH or K_3PO_4 in toluene (Scheme 5).[6d] The coupling of aryl chlorides, bromides and triflates is demonstrated in high yields. In these reactions, the bulkiness of the ligand is believed to be responsible for the acceleration of the rate of the reductive elimination of the diaryl ether from palladium.



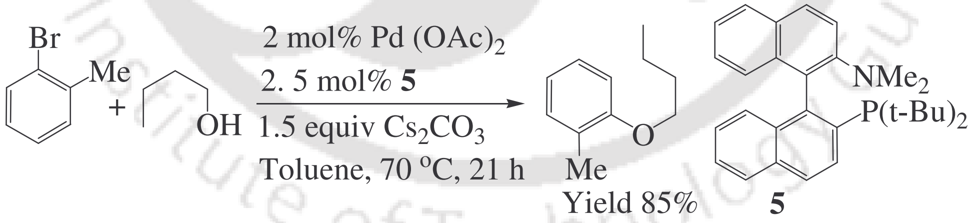
Scheme 5

Intramolecular C-O cross-coupling of hydroxy groups with aryl halides is accomplished using Pd(dba)$_2$-Ph$_5$FcP(*t*-Bu)$_2$ **4** in toluene at ambient temperature (Scheme 6).[6e] Turnovers of rougly 1000 are observed for reactions with unactivated aryl bromides or chlorides.



Scheme 6

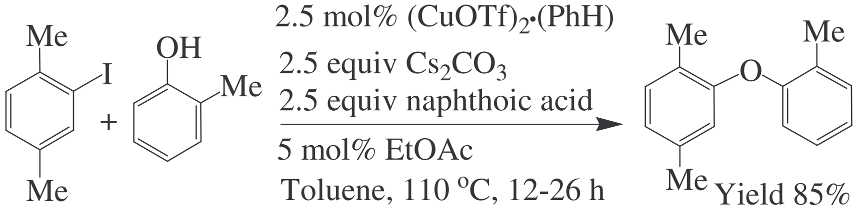
More recently, the coupling of alcohols with aryl bromides using Pd(OAc)$_2$ and ligand **5** is reported in the presence of Cs$_2$CO$_3$ at 70 °C in toluene (Scheme 7).[6f] Under these conditions, *n*-butanol undergoes reaction with 2-bromotoluene in 85% yield.



Scheme 7

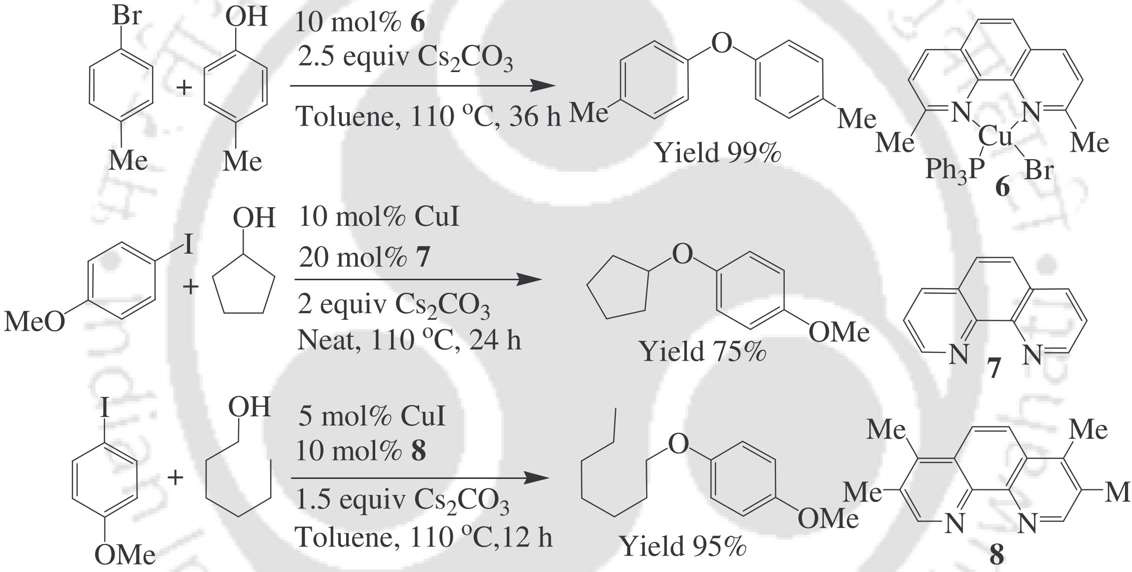
3.1.2 Copper Catalysts

Copper based catalytic systems are significantly studied for the *C-O* cross-coupling reactions.[7] The coupling of phenols with aryl iodides and -bromides is accomplished using (CuOTf)$_2$·benzene in the presence of Cs$_2$CO$_3$ in toluene (Scheme 8).[7a] In these reactions, 1-naphthoic acid enhances the solubility of the phenoxides.

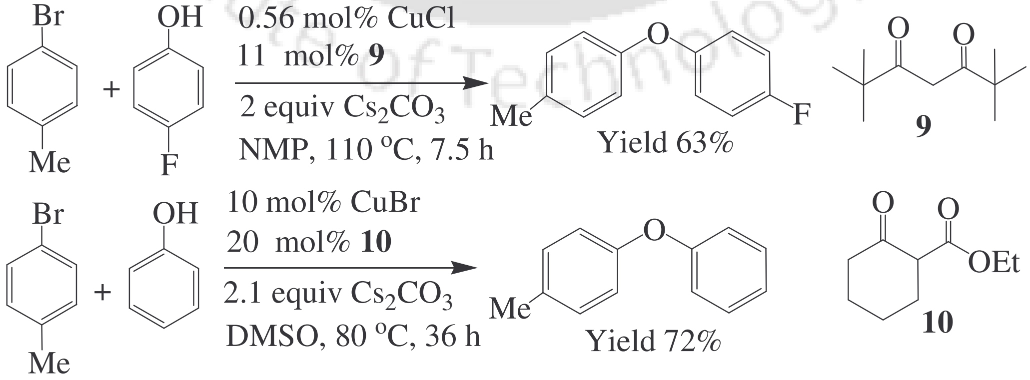


Scheme 8

The use of copper(I) salt in combination with phenanthroline based ligands **6-8** is described for the coupling of aryl iodides and –bromides with hydroxy compounds in the presence of Cs_2CO_3 (Scheme 9).[7b-d] Aryl iodides exhibited greater reactivity compared to aryl bromides. The reactions of phenols and primary alcohols are found to be successful under these conditions.

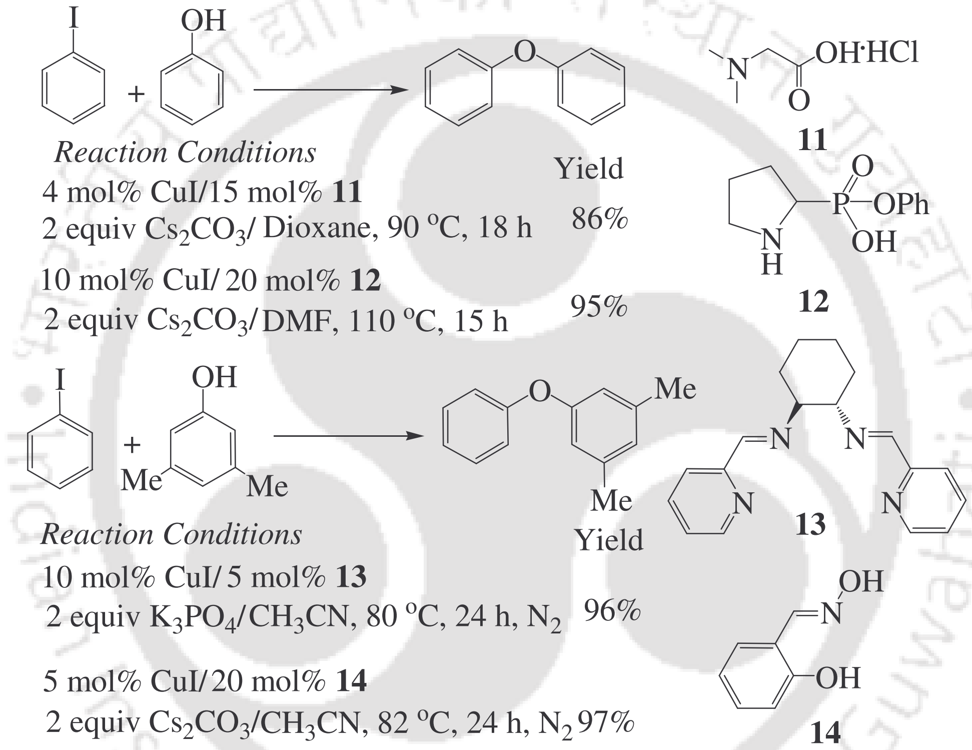


Scheme 9



Scheme 10

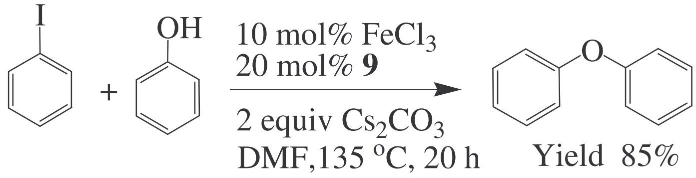
The coupling of aryl iodides and –bromides with hydroxy compounds is also demonstrated using copper(I) salt and 1,3-dicarbonyl compounds in the presence of Cs_2CO_3 under moderate temperature (Scheme 10).[7e-f] These reaction conditions are also suitable for the *C-N* and *C-S* cross-coupling reactions. Few studies are showed the coupling of phenols with aryl bromides and –iodides using CuI in combination with amino acid, amino phosphonate or imine as ligands in the presence of Cs_2CO_3 (Scheme 11).[7g-i] These reactions are effective at moderate temperature with high yields. Aryl iodides exhibited greater reactivity compared to aryl bromides.



Scheme 11

3.1.3 Iron Catalyst

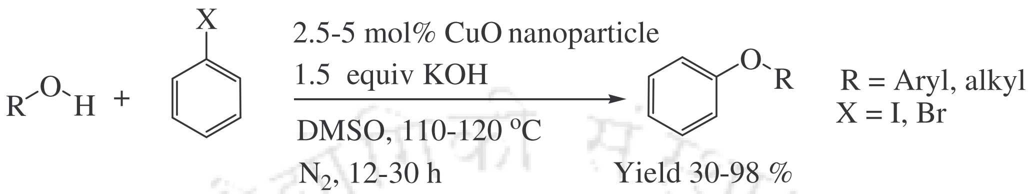
Iron(III) chloride in combination with 1,3-dicarbonyl compound **9** is used for the coupling of phenol with aryl iodide in the presence of Cs_2CO_3 in DMF (Scheme 12).[8] Aryl bromide is moderately reactive under these conditions.



Scheme 12

3. 2 Present Study

The coupling of hydroxy compounds with aryl iodide and -bromide is studied using CuO nanoparticle[9] in the presence of KOH in DMSO under ligand-free conditions (Scheme 13). Aryl and alkyl hydroxy compounds undergo reaction with high yields. The catalyst can be recovered and recycled without loss of actvitiy.



Scheme 13

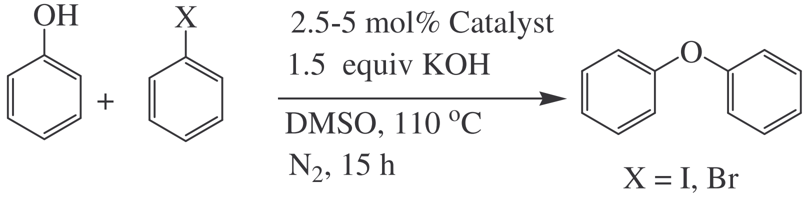
Table 1. Reaction of Phenol with Iodobenzene using Different Solvents and Bases

Entry	Solvent	Base	Diphenyl ether (Yield, %)[a]
1	DMSO	KOH	nr[b]
2	*i*-PrOH	KOH	45
3	DMSO	KOH	93
4	DMSO	K_2CO_3	40
5	DMF	KOH	13
6	Dioxane	KOH	nr
7	Toluene	KOH	41
8	DMSO	NEt_3	<5
9	DMSO	Pyridine	<10

[a] CuO nanoparticle (2.5 mol%), phenol (2.4 mmol), iodobenzene (2 mmol), base (3 mmol) and solvent (2 mL) were stirred at 110 °C for 15 h under N_2 atmosphere.

[b] Reaction was carried at room temperature for 24 h. nr = no reaction.

Table 2. Reaction of Phenol with Iodobenzene and Bromobenzene using Different Copper Sources



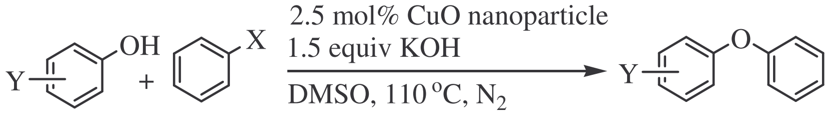
Entry	Catalyst	Aryl halide	Diphenyl ether (Yield,%)[a]
1	CuO nanoparticle	Iodobenzene	93
2	$CuSO_4 \cdot 5H_2O$	Iodobenzene	48
3	$Cu(OAc)_2 \cdot H_2O$	Iodobenzene	40
4	$CuCl_2 \cdot 2H_2O$	Iodobenzene	15
5	CuO	Iodobenzene	48
6	CuO nanoparticle	Bromobenzene	40[b]

[a] Catalyst (2.5 mol%), phenol (2.4 mmol), aryl halide (2 mmol) and KOH (3 mmol) were stirred in DMSO (2 mL) at 110 °C for 15 h under N_2 atmosphere.

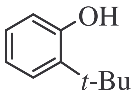
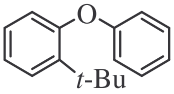
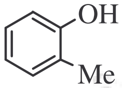
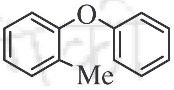
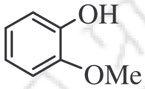
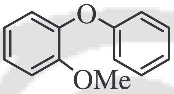
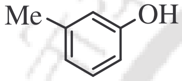
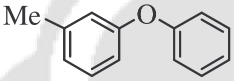
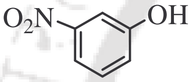
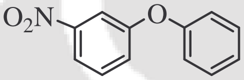
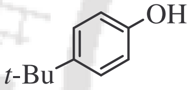
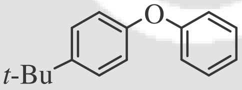
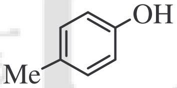
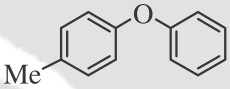
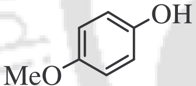
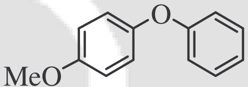
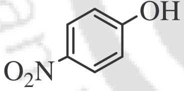
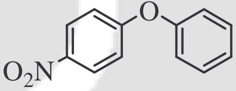
[b] Reaction was carried out with 5 mol% catalyst at 120 °C for 24 h.

First, the reaction of phenol with aryl iodide was studied as a model substrate (Table 1). The reaction occurred to afford the desired *C-O* cross-coupled diphenyl ether in 93% yield when the substrates were stirred at 110 °C for 15 h with 2.5 mol% of CuO nanoparticle and 1.5 equivalent of KOH in DMSO under nitrogen atmosphere. Of the solvents examined, DMSO, *i*-PrOH, DMF, 1,4-dioxane and toluene, the former provided the best result. In bases, KOH was more effective compared to K_2CO_3, pyridine and Et_3N. Among the copper(II) sources screened, CuO nanoparticle was superior to $CuSO_4 \cdot 5H_2O$, $Cu(OAc)_2 \cdot H_2O$, $CuCl_2 \cdot 2H_2O$ and CuO (Table 2). Aryl iodide exhibited greater reactivity compared to aryl bromide.

Table 3. Reactions of Substituted Phenols with Iodo- and –Bromobenzene



Y = EWG, EDG

Entry	Substrate	Product	X=I		X=Br	
			Time (h)	Yield (%)[a]	Time (h)	Yield (%)[b]
1			19	88	28	45
2			16	89	25	42
3			15	96	24	46
4			18	91	27	38
5			20	74	30	35
6			17	93	24	44
7			16	92	26	45
8			15	98	24	48
9			24	25	30	<5

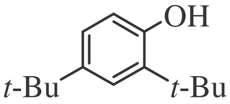
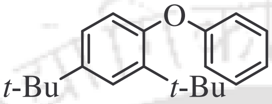
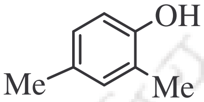
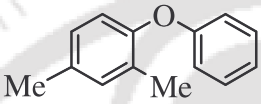
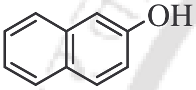
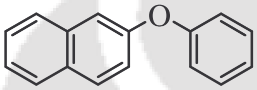
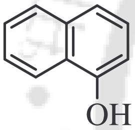
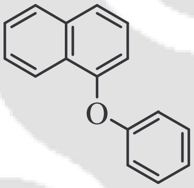
[a] CuO nanoparticle (2.5 mol%), phenol (2.4 mmol), aryl halide (2 mmol) and KOH (3 mmol) were stirred at 110 °C in DMSO (2 mL) under N_2 atmosphere.

[b] Catalyst (5 mol%) and temperature 120 °C used.

Next, the reaction of substituted phenols was investigated with aryl iodide and –bromide. Phenol having 2-*tert*-butyl, 2-methyl-, 2-methoxy-, 3-methyl-, 4-*tert*-butyl-, 4-methyl- and 4-methoxy substituents underwent reaction in 35-98% yield (Table 3). While 3- and 4-nitrophenols were less reactive affording the cross-coupled products in 74% and 25% yield, respectively. Similar results were observed with the reactions of disubstituted phenols and naphthol (Table 4). In these reactions, aryl iodide showed greater reactivity compared to aryl bromide. Phenols with electron donating group were more reactive compared to that having electron withdrawing group.

Table 4. Reaction of Naphthyl and Disubstituted Phenols with Iodo- and Bromobenzene

$$\text{ArOH} + \text{PhX} \xrightarrow[\text{DMSO, 110-120 }^{o}\text{C, N}_2]{\substack{\text{2.5-5 mol\% CuO nanoparticle}\\ \text{1.5 equiv KOH}}} \text{ArOPh} \qquad \text{X = I, Br}$$

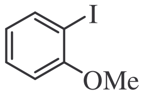
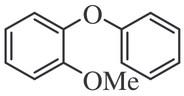
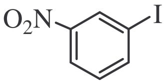
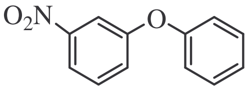
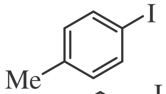
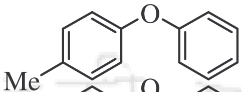
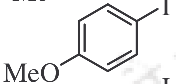
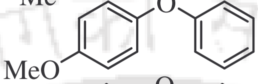
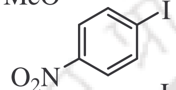
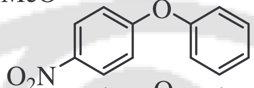
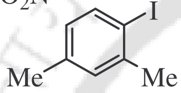
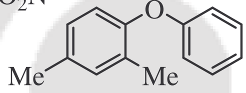
Entry	Substrate	Product	X=I		X=Br	
			Time (h)	Yield (%)[a]	Time (h)	Yield (%)[b]
1			21	88	30	32
2			18	90	28	44
3			14	89	22	35
4			14	91	24	40

[a] CuO nanoparticle (2.5 mol%), hydroxy compound (2.4 mmol), aryl halide (2 mmol) and KOH (3 mmol) were stirred at 110 °C in DMSO (2 mL) under N_2 atmosphere.

[b] Catalyst (5 mol%) and temperature 120 °C used.

Finally, the reaction of phenol was examined with substituted aryl iodides (Table 5). Aryl iodide having 2-methoxy-, 3-nitro-, 4-methyl-, 4-methoxy-, 4-nitro-, 2,3-dimethyl- and 2,4- dimethyl substituents underwent reaction in 70-98% yield. Aryl iodide with electron withdrawing group exhibited greater reactivity compared to that having electron donating group. These reaction conditions were also suitable for *C-O* cross-coupling aliphatic alcohols with aryl iodide and -bromide (Table 6). For examples, decanol, 2-ethyl-1-hexanol, pentaerythritol and triethanolamine underwent reaction with 30-92% yield.

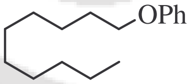
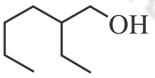
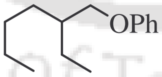
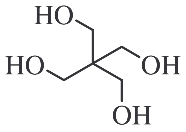
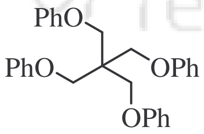
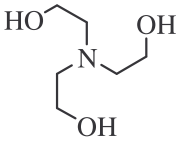
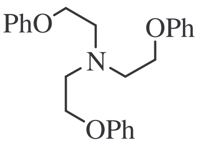
Table 5. Reaction of Phenol with Substituted Aryl Iodides

Entry	Aryl Iodide	Product	Time (h)	Yield (%)[a]
1			17	70
2			20	88
3			15	90
4			17	72
5			9	98
6			18	83

[a]CuO nanoparticle (2.5 mol%), phenol (2.4 mmol), aryl iodide (2 mmol) and KOH (3 mmol) were stirred at 110 °C in DMSO (2 mL) under N_2 atmosphere.

Table 6. CuO Nanoparticle Catalyzed Reaction of Alchols with Iodo- and -Bromobenzene

$$\text{ROH + PhX} \xrightarrow[\text{DMSO, 110-120 °C, N}_2]{\text{2.5-5 mol\% CuO nanoparticle} \atop \text{1.5 equiv KOH}} \text{ROPh} \quad \text{X = I, Br; R = Alkyl}$$

Entry	Substrate	Product	X= I		X= Br	
			Time (h)	Yield (%)[a]	Time (h)	Yield (%)[b]
1			14	77	24	32
2			17	85	24	30
3			21	92	24	41
4			16	90	24	38

[a]CuO Nanoparticle (2.5 mol%), alcohol (2.4 mmol), aryl halide (2 mmol) and KOH (3 mmol) were stirred at 110 °C in DMSO (2 mL) under N_2 atmosphere.

[b]Catalyst (5 mol%) and temperature 120 °C used.

Recyclability of CuO Nanoparticles

It is a heterogeneous process and the catalyst can be recovered and recycled (Table 7). After the completion of the reaction of phenol with iodobenzene, the reaction mixture was treated with water and ethyl acetate. The aqueous layer, after exctrating with ethyl acetate, was centrifuged and the CuO nanoparticle were recovered centrifugation and recycled for the fresh reaction of phenol with iodobenzene. This process was repeated up to three runs and the reactions occurred to afford the desired diphenyl ether in >90% yield.

Table 7. Recyclability of CuO Nanoparticle

$$\mathrm{PhOH + PhI} \xrightarrow[\substack{\text{DMSO, 110 }^{\circ}\text{C} \\ \text{N}_2\text{, 15 h}}]{\substack{\text{2.5 mol\% CuO nanoparticle} \\ \text{1.5 equiv KOH}}} \mathrm{PhOPh}$$

Run	Recoverability of CuO Nanoparticle (%)	PhOPh (Yield, %)
1[a]	96	93
2[b]	93	92
3[b]	90	90

[a] CuO nanoparticle (2.5 mol%), phenol (2.4 mmol), iodobenzene (2 mmol) and KOH (3 mmol) were stirred for 15 h at 110 °C in DMSO (2 mL) under N_2 atmosphere.

[b] Recovered CuO nanoparticle used.

Mechanism

The reactions of substituted aryl iodides with phenols suggest that this process takes place by oxidative addition followed by reductive elimination process as proposed in chapter I of the thesis. Phenol with aryl iodide having electron withdrawing group exhibited greater reactivity compared to that bearing electron donating group.

In conclusion, the *C-O* cross-coupling of hydroxy compounds with aryl halides is accomplished using CuO nanoparticles under ligand free conditions. The reaction is simple, general and variety of hydroxy compounds undergo reaction in high yields.

Experimental Section

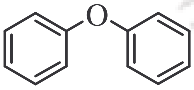
General. Hydroxy compounds were purchased from Aldrich.

General Procedure for *C-O* Cross-Coupling Reaction

Hydroxy compound (2.4 mmol), aryl halide (2 mmol), CuO nanoparticle (2.5-5 mol%) and KOH (3 mmol) were stirred in DMSO (2 mL) at 110-120 ^{o}C under N_2 atmosphere. The progress of the reaction was monitored by TLC using ethyl acetate and hexane as eluent. After completion, the reaction mixture was treated with ethyl acetate (10 mL) and water (3 mL). The organic layer was separated and the aqueous layer was extracted with ethyl acetate (3 x 5 mL). The combined organic solution was washed with brine (3 x 5 mL) and water (1 x 5 mL). Drying (Na_2SO_4) and evaporation of the solvent provided a residue which was purified on short pad of silica gel using ethyl acetate and hexane.

Recyclability of CuO Nanoparticles

A mixture of iodobenzene (2 mmol, mg), phenol (2.4 mmol, mg), CuO nanoparticles (2.5 mol%) and KOH (3 mmol, mg) was stirred at 80 ^{o}C under N_2 in DMSO (2 mL). The reaction mixture was treated with ethyl acetate (10 mL) and water (5 mL). The aqueous layer was separated and centrifuged with 10,000 rpm for an hour to provide the CuO nanoparticles. It was, after drying under vacuum, reused for the fresh reaction of thiophenol with iodobenzene for three recycles and no loss of activity observed.



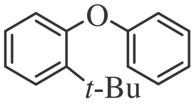
Diphenyl ether. Phenol (2.4 mmol, 225 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 15 h to afford diphenyl ether as colorless liquid in 93% (316 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.33 (m, 4H), 7.12-7.08 (m, 2H), 7.00 (m, 4H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.43, 129.94, 123.42, 119.08.

IR (neat): ν 3038, 2910, 2864, 1583, 1484, 1456, 1254, 1216, 1161, 1138, 1017, 935, 891, 864, 809, 757, 688, 655, 485 cm^{-1}.

Anal Calcd for $C_{12}H_{10}O$: C, 84.68; H, 5.92. Found: C, 84.66; H, 5.93.



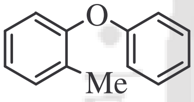
(2-*tert*-Butyl-phenyl) phenyl ether. 2-*t*-Butylphenol (2.4 mmol, 360 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 19 h to afford (2-*tert*- butyl-phenyl) phenyl ether as colorless liquid in 88% (398 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.40-7.38 (m, 1H), 7.33-7.29 (m, 2H), 7.12-7.10 (m, 1H), 7.06 -7.04 (m, 2H), 6.98-6.96 (m, 2H), 6.81 (d, J = 8.0 Hz, 1H), 1.41 (s, 9H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 157.97, 147.91, 129.86, 127.40, 127.29, 123.40, 122.81, 120.37, 118.86, 34.87, 30.31.

IR (KBr): ν 3038, 2960, 2872, 1588, 1506, 1492, 1363, 1237, 1171, 1108, 1017, 869, 836, 795, 749, 688, 540, 488 cm^{-1}.

Anal Calcd for $C_{16}H_{18}O$: C, 84.91; H, 8.02. Found C, 84.95; H, 8.04.



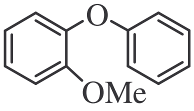
2-Tolyl phenyl ether. 2-Methylphenol (2.4 mmol, 259 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 16 h to afford *o*-tolylphenyl ether as colorless oil in 89% (327 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.30-7.22 (m, 3H), 7.14-7.07 (m, 1H), 7.08-6.99 (m, 3H), 6.90-6.88 (m, 2H), 2.23 (s, 3H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 158.11, 154.63, 131.65, 129.86, 127.66, 127.35, 124.21, 122.53, 120.00, 119.09, 117.48. 16.40.

IR (neat): ν 3038, 2917, 2862, 1583, 1484, 1456, 1253, 1215, 1160, 1138, 1017, 935, 891, 864, 809, 757, 688, 655, 485 cm^{-1}.

Anal Calcd for $C_{13}H_{12}O$: C, 84.75; H, 6.57. Found: C, 84.73; H, 6.58.



***o*-Anisyl phenyl ether.** 2-Methoxy phenol (2.4 mmol, 297 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 15 h to afford *o*-anisyl phenyl ether as yellow solid in 96% (384 mg) yield.

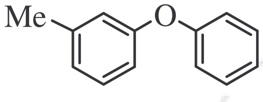
Mp: 75 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.31-7.25 (m, 2H), 7.13 (t, *J* = 8.4 Hz, 1H), 7.06-6.89 (m, 6H), 3.84 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.97, 151.43, 145.16, 129.71, 124.98, 122.68, 121.29, 117.43, 112.96, 56.16.

IR (KBr): ν 2840, 2936, 1595, 1493, 1456, 1294, 1261, 1222, 1195, 1172, 1151, 1110, 1040, 1021, 869, 798, 770, 749, 688 cm^{-1}.

Anal Calcd for $C_{13}H_{12}O_2$: C, 77.98; H, 6.04. Found: C, 78.02; H, 6.05.



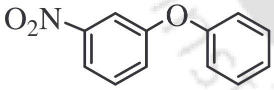
3-Tolyl phenyl ether. 3-Methylphenol (2.4 mmol, 259 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 18 h to afford 3-tolyl phenyl ether as colorless oil in 91% (334 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.34-7.30 (m, 2H), 7.23-7.18 (m, 1H), 7.10-7.06 (m, 1H), 7.01-6.99 (m, 2H), 6.92 (m, 1H), 6.83-6.80 (m, 2H), 2.32 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.54, 157.37, 137.69, 129.90, 129.64, 124.25, 123.28, 119.77, 119.05, 116.11, 21.60.

IR (neat): ν 3038, 2917, 2863, 1583, 1480, 1456, 1252, 1215, 1164, 1138, 1016, 935, 895, 864, 804, 757, 688, 651, 482 cm^{-1}.

Anal Calcd for $C_{13}H_{12}O$: C, 84.75; H, 6.57. Found: C, 84.73; H, 6.58.



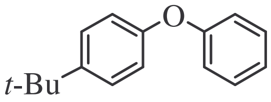
(3-Nitrophenyl) phenyl ether. 3-Nitrophenol (2.4 mmol, 333 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 20 h to afford (3-nitrophenyl) phenyl ether as colorless oil in 74% (318 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.87 (d, *J* = 8.4 Hz, 1H), 7.60 (t, *J* = 8.07 Hz, 1H), 7.32–7.21 (m, 3H), 7.04 (t, *J* = 7.6 Hz, 1H), 6.94-6.90 (m, 2H), 6.81 (d, *J* = 8.4 Hz, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 158.62, 155.64, 149.54, 130.80, 129.85, 124.48, 122.27, 120.90, 116.55, 115.49.

IR (neat): ν 3378, 3093, 2954, 1590, 1582, 1501, 1486, 1345, 1251, 1196, 1157, 1109, 1020, 871, 847, 795, 746, 686 cm^{-1}.

Anal Calcd for $C_{12}H_9NO_3$: C, 66.97; H, 4.22; N, 6.51. Found C, 67.94; H, 4.25; N, 6.53.



(4-*tert*-Butyl-phenyl) phenyl ether. 4-*tert*-Butyl phenol (2.4 mmol, 360 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 17 h to to afford (4-*tert*- butyl-phenyl) phenyl ether as colorless solid in 93% (420 mg) yield.

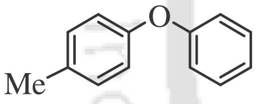
Mp: 55 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.34-7.27 (m, 4H), 7.05 (m, 1H), 7.00-6.98 (m, 2H), 6.94-6.92 (m, 2H), 1.31 (s, 9H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.77, 154.88, 146.28, 129.92, 126.74, 123.40, 119.07, 118.80, 34.50, 31.70.

IR (KBr): ν 3038, 2961,2870, 1587, 1506, 1492, 1363, 1238, 1171, 1108, 1017, 864, 836, 792, 741, 6868, 541, 483 cm^{-1}.

Anal Calcd for $C_{16}H_{18}O$: C, 84.91; H, 8.02. Found C, 84.90; H, 8.05.



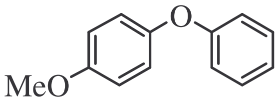
***p*-Tolyl phenyl ether.** 4-Methylphenol (2.4 mmol, 259 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 16 h to afford *p*-tolyl phenyl ether as colorless oil in 92% (338 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.33-7.29 (m, 2H), 7.14-7.12 (m, 2H), 7.10-7.06 (m, 1H), 6.99-6.93 (m, 2H), 6.92-6.89 (m, 2H), 2.33 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 158.27, 154.89, 133.12, 130.44, 129.85, 123.0, 119.06, 118.54, 22.92.

IR (neat): ν 3037, 2918, 2864, 1583, 1482, 1455, 1253, 1216, 1164, 1139, 1016, 935, 894, 864, 801, 757, 688, 653, 480 cm^{-1}.

Anal Calcd for $C_{13}H_{12}O$: C, 84.75; H, 6.57. Found: C, 84.73; H, 6.58.



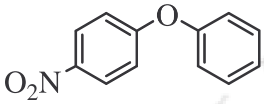
***p*-Anisyl phenyl ether.** 4-Methoxy phenol (2.4 mmol, 297 mg), Iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 15 h to afford *p*-anisyl phenyl ether as colorless oil in 98% (392 mg) yield.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 7.30-7.26 (m, 2H), 7.02-6.86 (m, 7H), 3.78 (s, 3H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 158.70, 156.06, 150.27, 129.79, 122.60, 121.03, 119.06, 117.74, 115.02, 55.81.

IR (neat): ν 2840, 2935, 1592, 1491, 1456, 1293, 1261, 1220, 1194, 1170, 1151, 1113, 1040, 1022, 869, 798, 773, 744, 680 cm^{-1}.

Anal Calcd for $C_{13}H_{12}O_2$: C, 77.98; H, 6.04. Found: C, 77.95; H, 6.05.



(4-Nitrophenyl) phenyl ether. 4-Nitrophenol (2.4 mmol, 333 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 24 h to afford (4-nitrophenyl) phenyl ether as yellow solid in 25% (77 mg) yield.

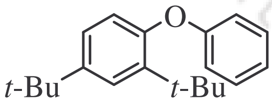
Mp: 56 °C.

^{1}H NMR (CDCl$_3$, 400 MHz) δ 8.10 (dd, J = 9.2 Hz, 2.0 Hz, 2H), 7.35 (t, J = 6.4 Hz, 2H), 7.18 (t, J = 8.0 Hz, 1H), 7.00 (d, J = 8.4 Hz, 2H), 6.91 (d, J = 9.6 Hz, 2H).

^{13}C NMR (CDCl$_3$, 100 MHz) δ 163.56, 154.84, 142.74, 130.51, 126.13, 125.61, 120.74, 117.25.

IR (KBr): ν 3379, 3093, 2956, 1596, 1583, 1506, 1486, 1341, 1251, 1193, 1157, 1105, 1020, 872, 847, 795, 749, 688 cm^{-1}.

Anal Calcd for $C_{12}H_9NO_3$: C, 66.97; H, 4.22; N, 6.51. Found: C, 67.94; H, 4.25; N, 6.50.



(2,4-Di-*tert*-butyl-phenyl) phenyl ether. 2,4-Di-*tert*-butyl phenol (2.4 mmol, 494 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 21 h to afford (2, 4-di-*tert*-butyl-phenyl) phenyl ether as colorless solid in 88% (496 mg) yield.

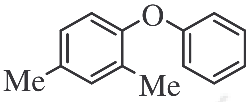
Mp: 48-50°C.

^{1}H NMR ($CDCl_{3,}$ 400 MHz) δ 7.40 (s, 1H), 7.30 (t, *J* = 7.6 Hz, 2H), 7.11 (d, *J*= 9.2 Hz, 1H), 7.04 (t, *J* = 7.6 Hz, 1H), 6.96 (d, *J* = 7.6 Hz, 2H), 6.73 (d, *J* = 8.8 Hz, 1H), 1.41 (s, 9H), 1.32 (s, 9H),

^{13}C NMR ($CDCl_{3,}$ 100 MHz) δ 158.71, 157.77, 140.14, 129.79, 124.31, 123.99, 122.55, 119.76, 118.72, 35.15, 31.80, 30.42, 29.88.

IR (KBr): ν 3066, 2961, 2924, 2872, 1596, 1486, 1396, 1860, 1160, 1119, 1086, 1023, 886, 853, 828, 749, 691 cm^{-1}.

Anal Calcd for $C_{20}H_{26}O$: C, 85.06; H, 9.28. Found: C, 85.00; H, 9.25.



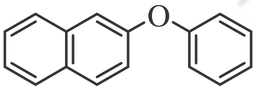
(2,4-Dimethylphenyl) phenyl ether. 2,4-Di-methyl phenol (2.4 mmol, 293 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction conditions described in the general procedure for 18 h to afford (2,4-dimethylphenyl) phenyl ether as colorless oil in 90% (356 mg) yield.

^{1}H NMR ($CDCl_{3,}$ 400 MHz) δ 7.29-7.24 (m, 2H), 7.05-6.95 (m, 4H), 6.88-6.81 (m, 2H), 2.31 (s, 3H), 2.28 (s, 3H).

^{13}C NMR ($CDCl_{3,}$ 100 MHz) δ 158.52, 148.85, 132.09, 129.77, 127.85, 127.51, 125.18, 122.15, 120.34, 117.58, 116.95, 116.79, 20.95, 16.30.

IR (KBr): ν 3329, 2958, 2923, 2869, 1589, 1487, 1251, 1218, 1119, 1097, 1032, 850, 825, 803, 752 cm^{-1}.

Anal Calcd for $C_{14}H_{14}O$: C, 84.81; H, 7.12. Found: C, 84.79; H, 7.15.



2-Phenoxynaphthalene. 2-Naphthol (2.4 mmol, 347 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 14 h to afford 2-phenoxynaphthalene as colorless solid in 89% (391 mg) yield.

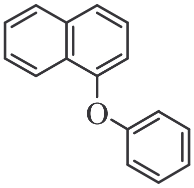
Mp: 46°C.

^{1}H NMR ($CDCl_{3,}$ 400 MHz) δ 7.83-7.80 (m, 2H), 7.69 (d, *J* = 8.4 Hz, 1H,), 7.44-7.30 (m, 6H), 7.15-6.99 (m, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.18, 155.27, 134.51, 130.07, 129.93, 127.93, 127.32, 126.71, 124.89, 123.64, 123.41, 120.18, 119.08, 114.26.

IR (KBr): ν 3373, 3054, 2956, 2917, 2851, 1626, 1591, 1574, 1506, 1486, 1459, 1388, 1259, 1231, 1209, 1157, 1075, 1042, 1015, 886, 861, 790, 770, 751, 688, 474 cm^{-1}.

Anal Calcd for $C_{16}H_{12}O$: C, 87.25; H, 5.49. Found C, 87.30; H, 5.52.



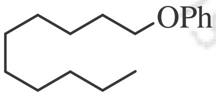
1-Phenoxynaphthalene. 1-Naphthol (2.4 mmol, 347 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 14 h to afford 1-phenoxynaphthalene as viscous liquid in 91% (400 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.18 (d, *J* = 8.0 Hz, 1H), 7.85 (d, *J* = 7.6 Hz, 1H), 7.53-7.47 (m, 2H), 7.39-7.30 (m, 4H), 7.12-6.99 (m, 3H), 6.93 (d, *J* = 7.6 Hz, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.96, 153.20, 135.12, 130.00, 127.96. 126.80, 126.14, 126.00, 123.56, 123.34, 122.30. 119.08, 118.74, 113.69.

IR (neat): ν 3373, 3054, 2953, 2917, 2853, 1621, 1591, 1575, 1506, 1486, 1461, 1388, 1257, 1231, 1210, 1157, 1075, 1048, 1015, 889, 861, 794, 770, 7541, 689, 479 cm^{-1}.

Anal Calcd for $C_{16}H_{12}O$: C, 87.25; H, 5.49. Found: C, 87.27; H, 5.48.



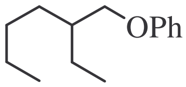
***n*-Decyl phenyl ether.** *n*-Decanol (2.4 mmol, 379 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 14 h to afford *n*-decyl phenyl ether as colorless oil in 77% (360 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.29 -7.25 (m, 2H), 6.93-6.88 (m, 3H), 3.94 (t, *J* = 6.4 Hz, 2H), 1.79-1.75 (m, 2H), 1.46-1.27 (m, 14H), 0.88 (t, *J* = 6.4 Hz, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 159.32, 129.60, 120.63, 114.68, 68.07, 32.11, 29.77, 29.62, 29.54, 29.51, 26.27, 22.90, 14.33.

IR (neat): ν 3038, 2923, 2851, 1599, 1585, 1495, 1467, 1385, 1297, 1286, 1242, 1168, 1078, 1039, 751, 688, 661 cm^{-1}.

Anal Calcd for $C_{16}H_{26}O$: C, 81.99; H, 11.18. Found: C, 81.90; H, 11.21.



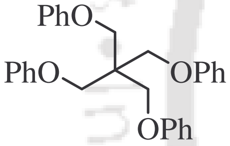
(2-Ethyl-hexyl) phenyl ether. 2-Ethyl-hexanol (2.4 mmol, 312 mg), iodobenzene (2 mmol, 406 mg), KOH (3 mmol, 168 mg), CuO nanoparticle (2.5 mol%, 4 mg) and DMSO (1 mL) were subjected to the reaction condition described in the general procedure for 17 h to afford (2-ethyl-hexyl) phenyl ether as colorless oil in 85% (350 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.28 -7.24 (m, 2H), 6.93-6.88 (m, 3H), 3.83 (d, *J* = 6.0 Hz, 2H), 1.80-1.60 (m, 1H), 1.52-1.29 (m, 8H), 0.94-0.88 (m, 6H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 159.59, 129.57, 120.55, 114.71, 70.54, 39.59, 30.74, 29.29, 24.06, 23.28, 14.31, 11.32.

IR (neat): ν 3064, 3041, 2959, 2932, 2876, 2859, 1602, 1585, 1495, 1467, 1382, 1300, 1286, 1245, 1171, 1075, 1034, 877, 809, 751, 691 cm^{-1}.

Anal Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.75. Found: C, 81.53; H, 10.77.



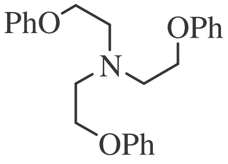
1,3-Diphenoxy-2,2-bis(phenoxymethyl)-propane. Pentaerythrtol (1.2 mmol, 162 mg), iodobenzene (4 mmol, 824 mg), KOH (6 mmol, 336 mg), CuO nanoparticle (5 mol%, 8 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 21 h to afford 1, 3-diphenoxy-2,2-bis(phenoxymethyl)-propane as colorless gummy oil in 92% (404 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.28 -7.25 (m, 8H), 6.95-6.91 (m, 12H), 4.36 (s, 8H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 157.32, 129.64, 121.19, 114.88, 66.70, 39.59.

IR (neat): ν 3046, 2929, 1599, 1588, 1492, 1467, 1297, 1256, 1240, 1171, 1075, 1037, 875, 850, 798, 749, 688, 658 cm^{-1}.

Anal Calcd for $C_{29}H_{28}O_4$: C, 79.07; H, 6.41. Found: C, 79.05; H, 6.42.



(2,2′,2″-Triphenoxy) triethyl amine. Triethanol amine (1.2 mmol, 178 mg), iodobenzene (3 mmol, 618 mg), KOH (4.5 mmol, 252 mg), CuO nanoparticle (5 mol%, 4 mg) and DMSO (2 mL) were subjected to the reaction condition described in the general procedure for 16 h to afford (2,2',2''-triphenoxy)triethyl amine as colorless oil in 93% (350 mg) yield.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.30 -7.26 (m, 6H), 6.96 (t, *J* = 6.8 Hz, 3H), 6.88 (d, *J* = 9.2 Hz, 6H), 4.06 (t, *J* = 5.2 Hz, 6H), 3.08 (t, *J* = 5.2 Hz, 6H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 158.68, 129.63, 121.03, 114.62, 66.28, 57.06.

IR (neat): ν 3439, 3061, 3040, 2923, 2862, 1720, 1591, 1470, 1399, 1360, 1330, 1292, 1234, 1166, 1078, 1037, 902, 886, 787, 754, 691, 614, 507 cm^{-1}.

Anal Calcd for $C_{24}H_{27}NO_3$: C, 76.36; H, 7.21; N, 3.71; Found C, 76.22; H, 7.20; N, 3.72.

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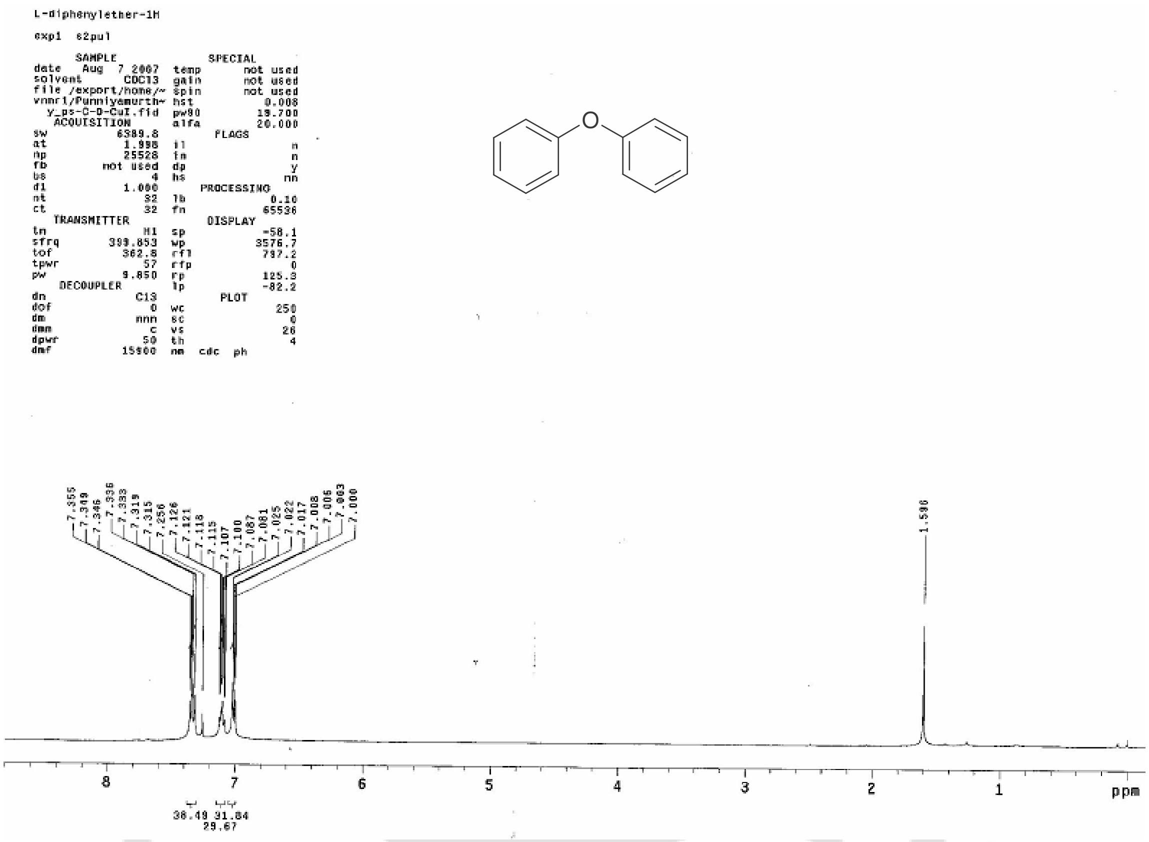

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vnmr1/Punniyamurth~   hst              0.008
  y_ps-C-O-CuI.fid    pw90            19.700
     ACQUISITION      alfa            20.000
sw           6389.8            FLAGS
at            1.998   il                   n
np            25528   in                   n
fb         not used   dp                   y
bs                4   hs                  nn
d1            1.000          PROCESSING
nt               32   lb                0.10
ct               32   fn               65536
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sfrq        399.853   wp              3576.7
tof           362.8   rfl              797.2
tpwr             57   rfp                  0
pw            9.850   rp               125.3
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dn              C13             PLOT
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dm              nnn   sc                   0
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dmf           15900   nm   cdc   ph
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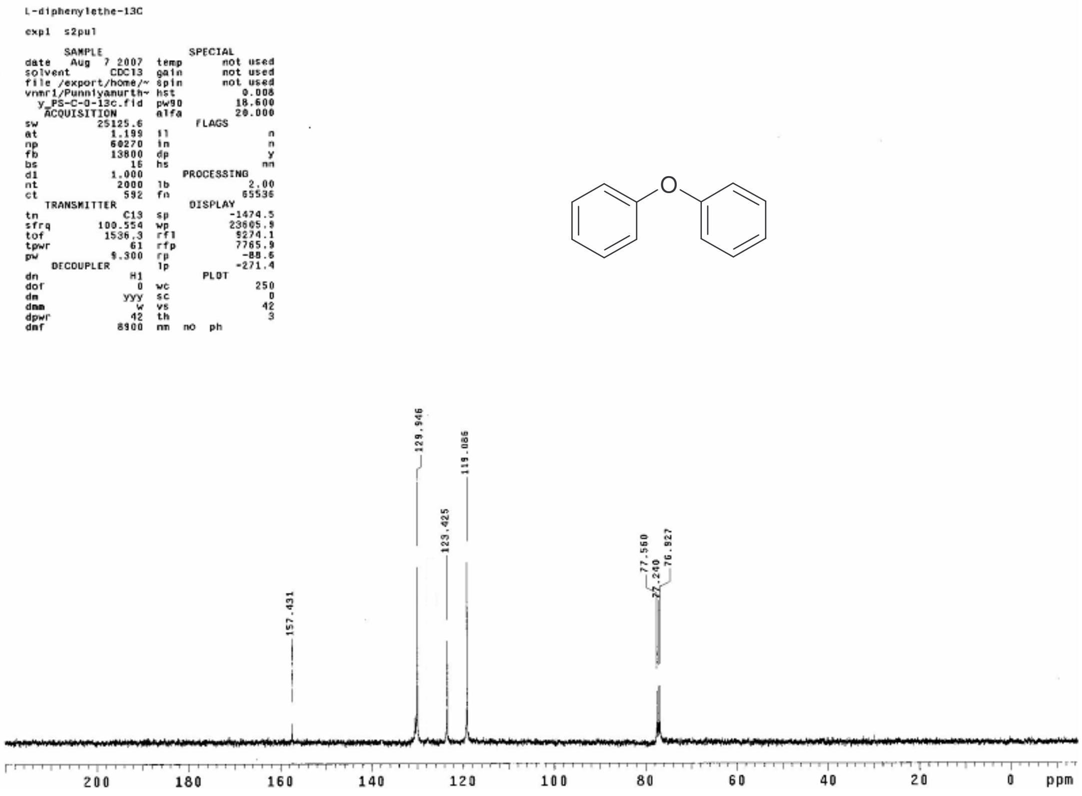

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L-diphenylethe-13C

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solvent       CDC13   gain          not used
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vnmr1/Punniyamurth~   hst              0.008
  y_PS-C-O-13c.fid    pw90            18.600
     ACQUISITION      alfa            20.000
sw          25125.6            FLAGS
at            1.199   il                   n
np            60270   in                   n
fb            13800   dp                   y
bs               16   hs                  nn
d1            1.000          PROCESSING
nt             2000   lb                2.00
ct              592   fn               65536
     TRANSMITTER              DISPLAY
tn              C13   sp             -1474.5
sfrq        100.554   wp             23605.9
tof          1536.3   rfl             9274.1
tpwr             61   rfp             7765.9
pw            9.300   rp               -88.6
      DECOUPLER       lp              -271.4
dn               H1             PLOT
dof               0   wc                 250
dm              yyy   sc                   0
dmm               w   vs                  42
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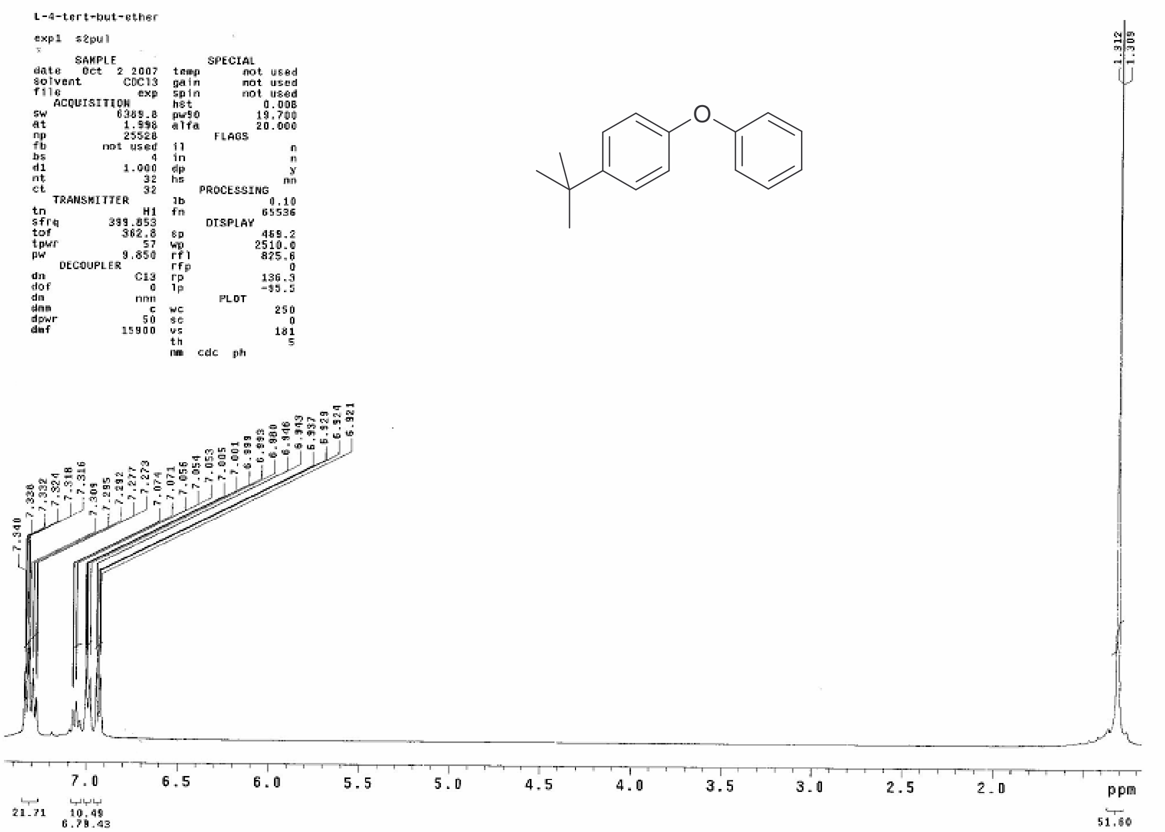

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L-4-tert-but-ether

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file               exp   spin          not used
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at               1.998   alfa            20.000
np               25528             FLAGS
fb            not used   il                   n
bs                   4   in                   n
d1               1.000   dp                   y
nt                  32   hs                  nn
ct                  32          PROCESSING
    TRANSMITTER          lb                0.10
tn                  H1   fn               65536
sfrq           399.853            DISPLAY
tof              362.8   sp               469.2
tpwr                57   wp              2510.0
pw               9.850   rfl              825.6
     DECOUPLER           rfp                  0
dn                 C13   rp               136.3
dof                  0   lp               -35.5
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dpwr                50   sc                   0
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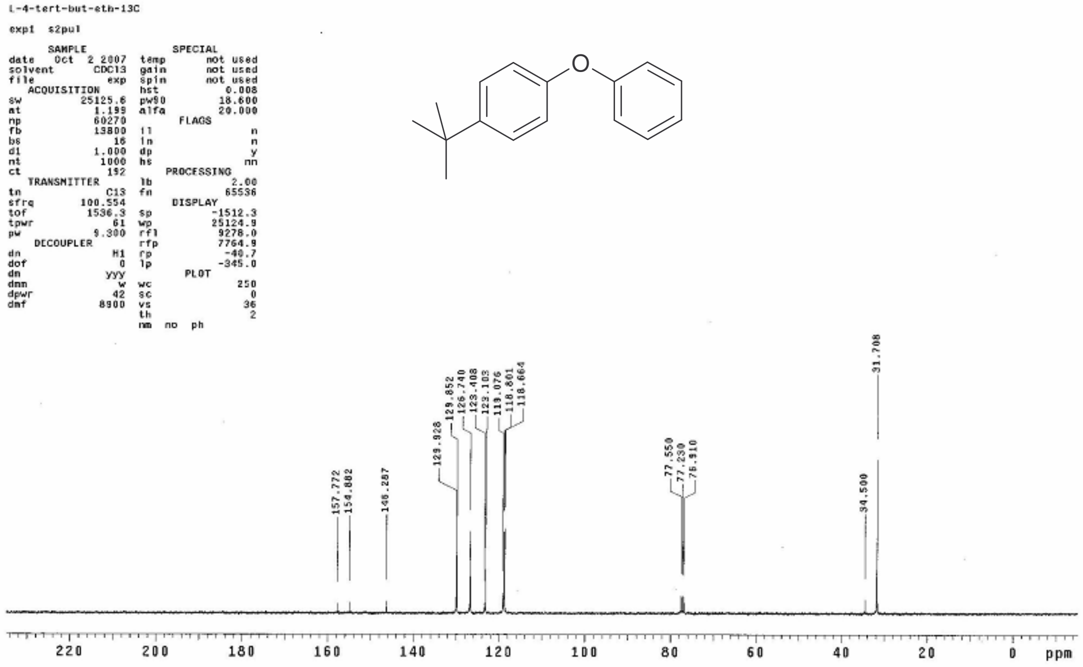

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file               exp   spin          not used
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sw             25125.6   pw90            18.600
at               1.199   alfa            20.000
np               60270             FLAGS
fb               13800   il                   n
bs                  16   in                   n
d1               1.000   dp                   y
nt                1000   hs                  nn
ct                 192          PROCESSING
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tn                 C13   fn               65536
sfrq           100.554            DISPLAY
tof             1536.3   sp             -1512.3
tpwr                61   wp             25124.9
pw               9.300   rfl             9278.0
     DECOUPLER           rfp             7764.9
dn                  H1   rp               -40.7
dof                  0   lp              -345.0
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                         th                   2
                         nm   no   ph
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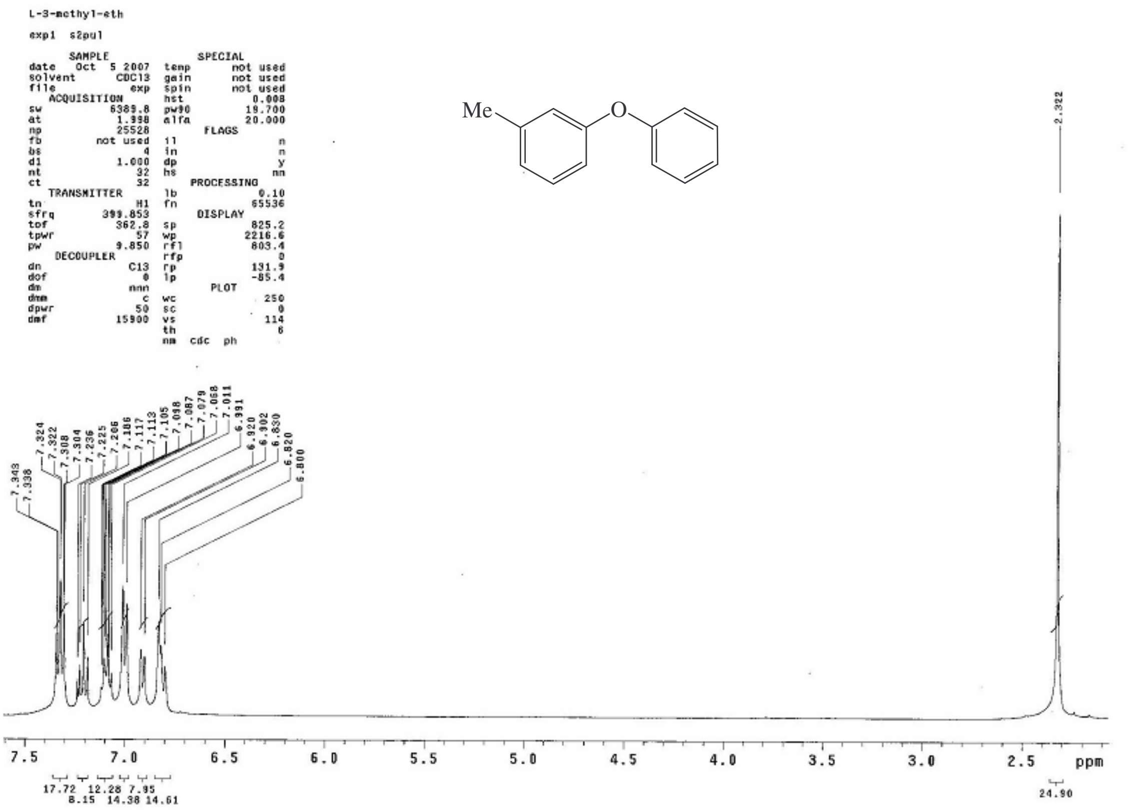

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at              1.998   alfa           20.000
np              25528            FLAGS
fb           not used   il                  n
bs                  4   in                  n
d1              1.000   dp                  y
nt                 32   hs                 nn
ct                 32          PROCESSING
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tn                 H1   fn              65536
sfrq          399.853           DISPLAY
tof             362.8   sp              825.2
tpwr               57   wp             2216.6
pw              9.850   rfl             803.4
     DECOUPLER          rfp                 0
dn                C13   rp              131.9
dof                 0   lp              -85.4
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                        nm   cdc   ph
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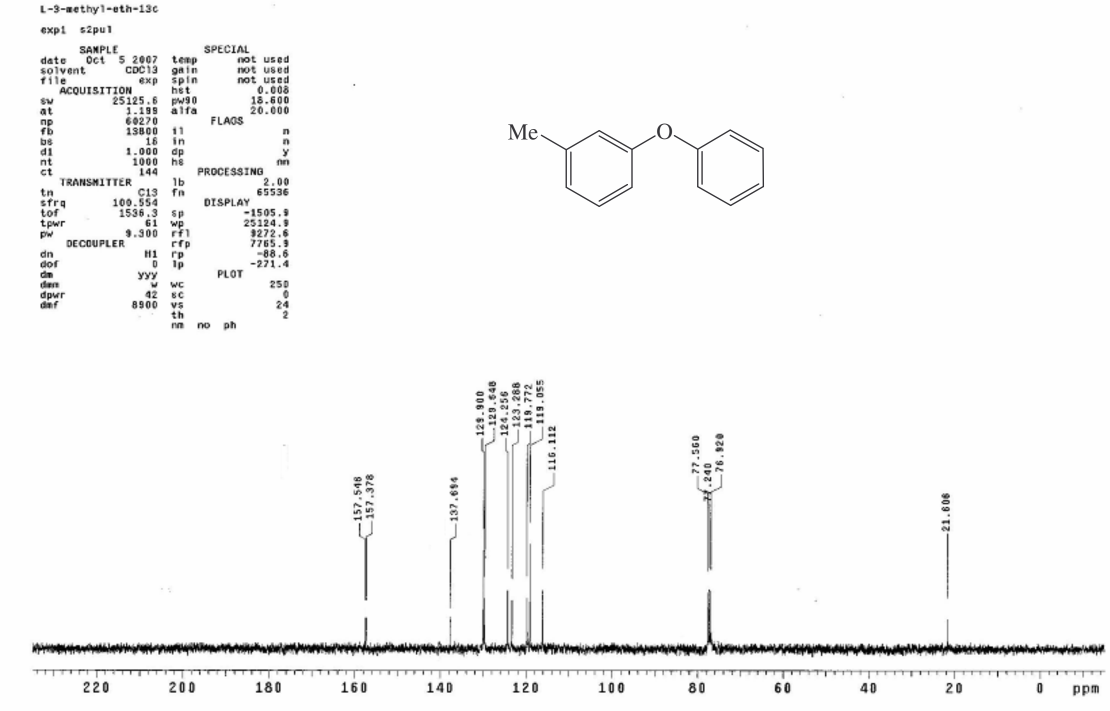

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L-3-methyl-eth-13c

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at              1.199   alfa           20.000
np              60270            FLAGS
fb              13800   il                  n
bs                 16   in                  n
d1              1.000   dp                  y
nt               1000   hs                 nn
ct                144          PROCESSING
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tpwr               61   wp            25124.9
pw              9.300   rfl            9272.6
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dn                 H1   rp              -88.6
dof                 0   lp             -271.4
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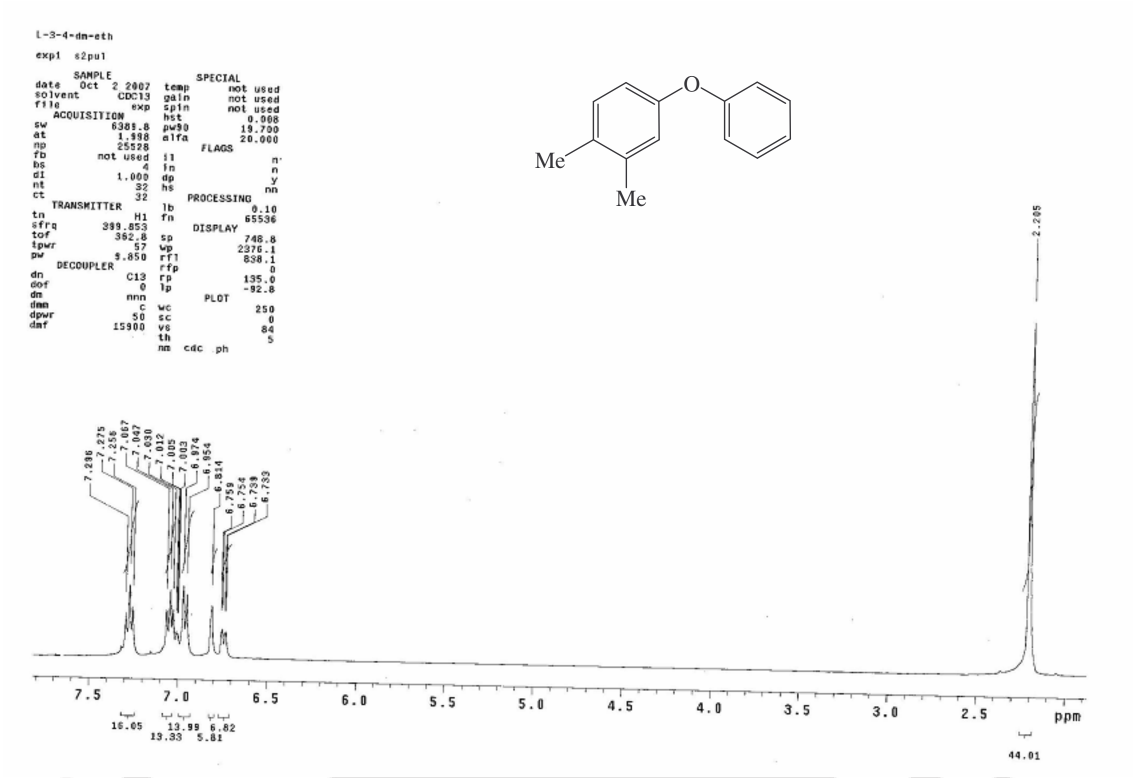
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spin not used
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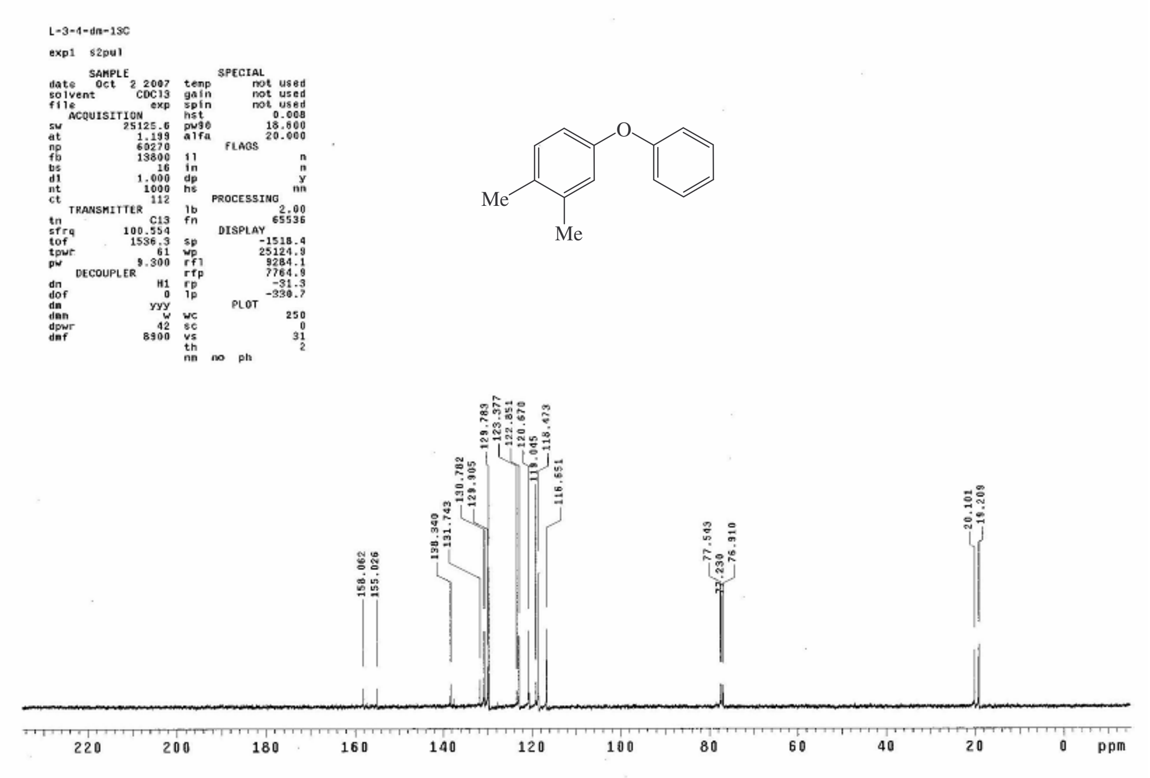
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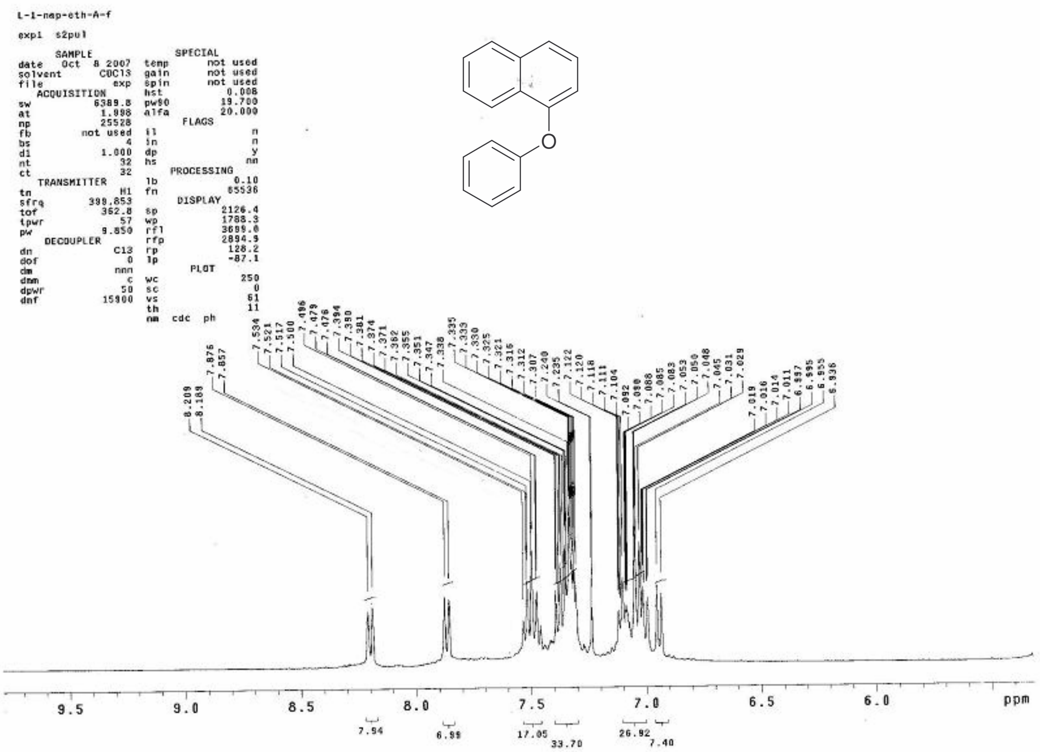
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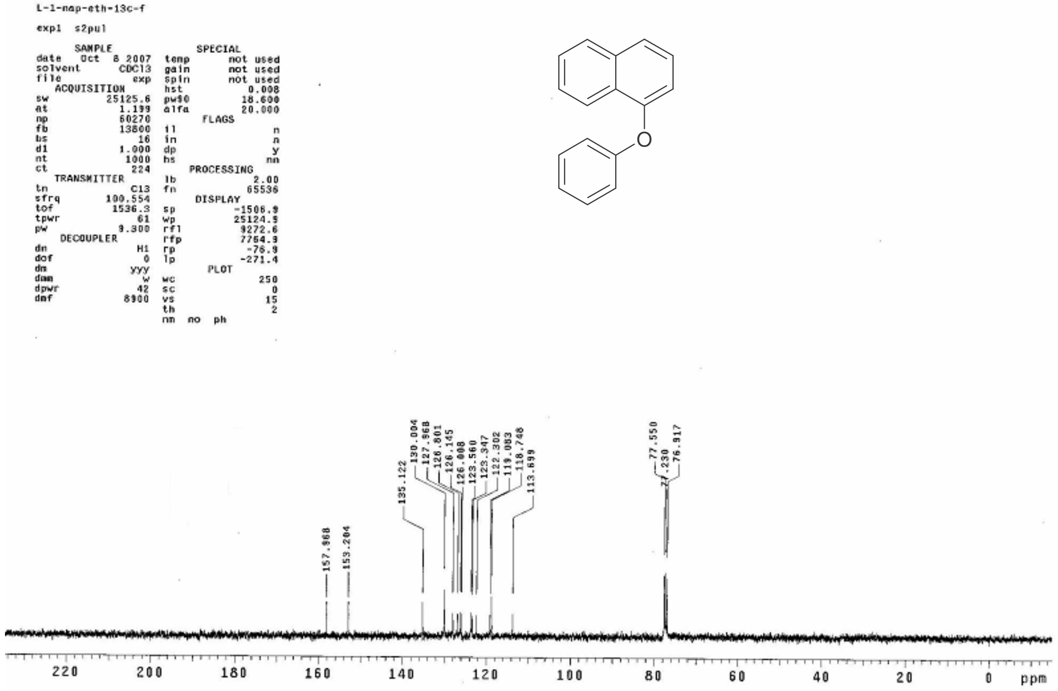
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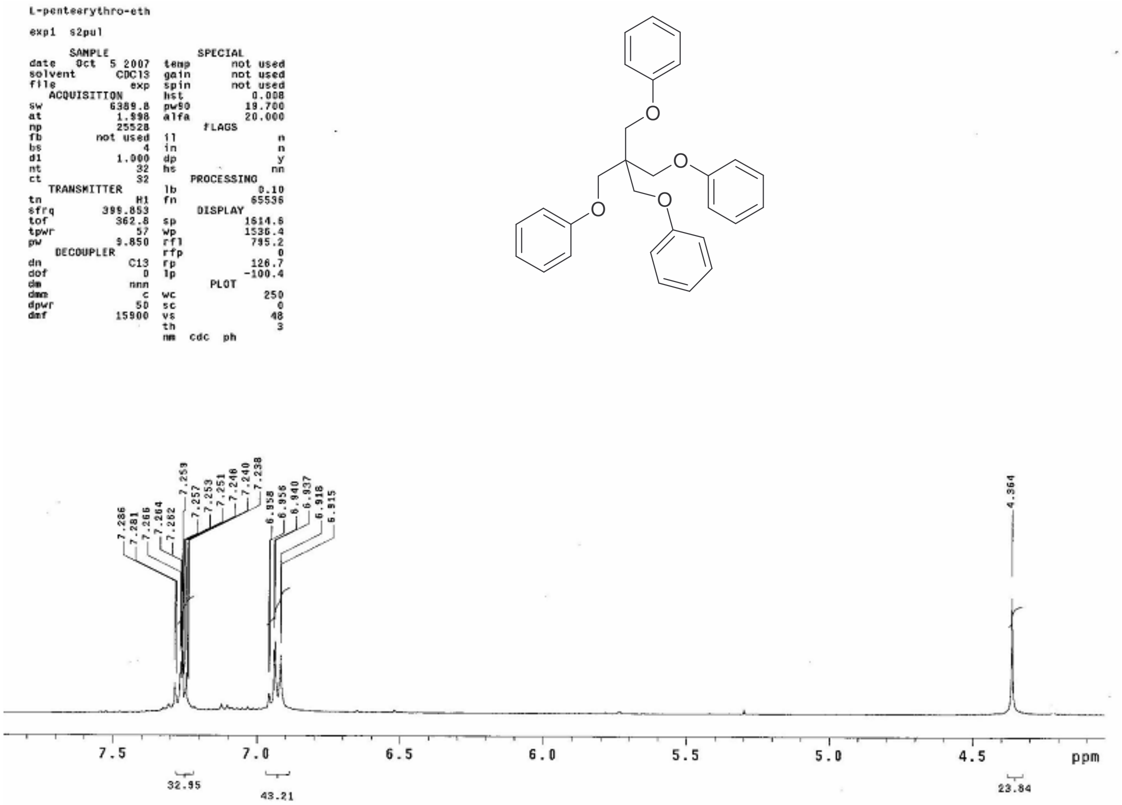

```
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np            25528          FLAGS
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bs                4  in                n
d1            1.000  dp                y
nt               32  hs               nn
ct               32        PROCESSING
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tpwr             57  wp           1536.4
pw            9.850  rfl           795.2
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dn              C13  rp            126.7
dof               0  lp           -100.4
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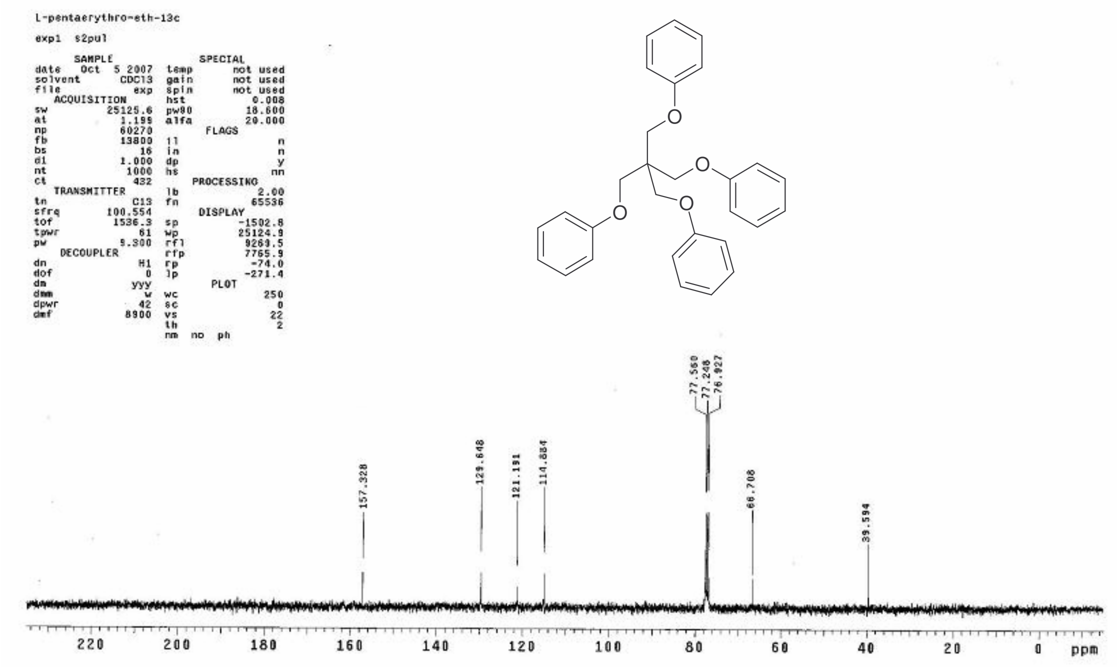

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L-pentaerythro-eth-13c

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at            1.199  alfa         20.000
np            60270          FLAGS
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bs               16  in                n
d1            1.000  dp                y
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ct              432        PROCESSING
   TRANSMITTER       lb             2.00
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sfrq        100.554         DISPLAY
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tpwr             61  wp          25124.9
pw            9.300  rfl          9269.5
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                     th                2
                     nm   no   ph
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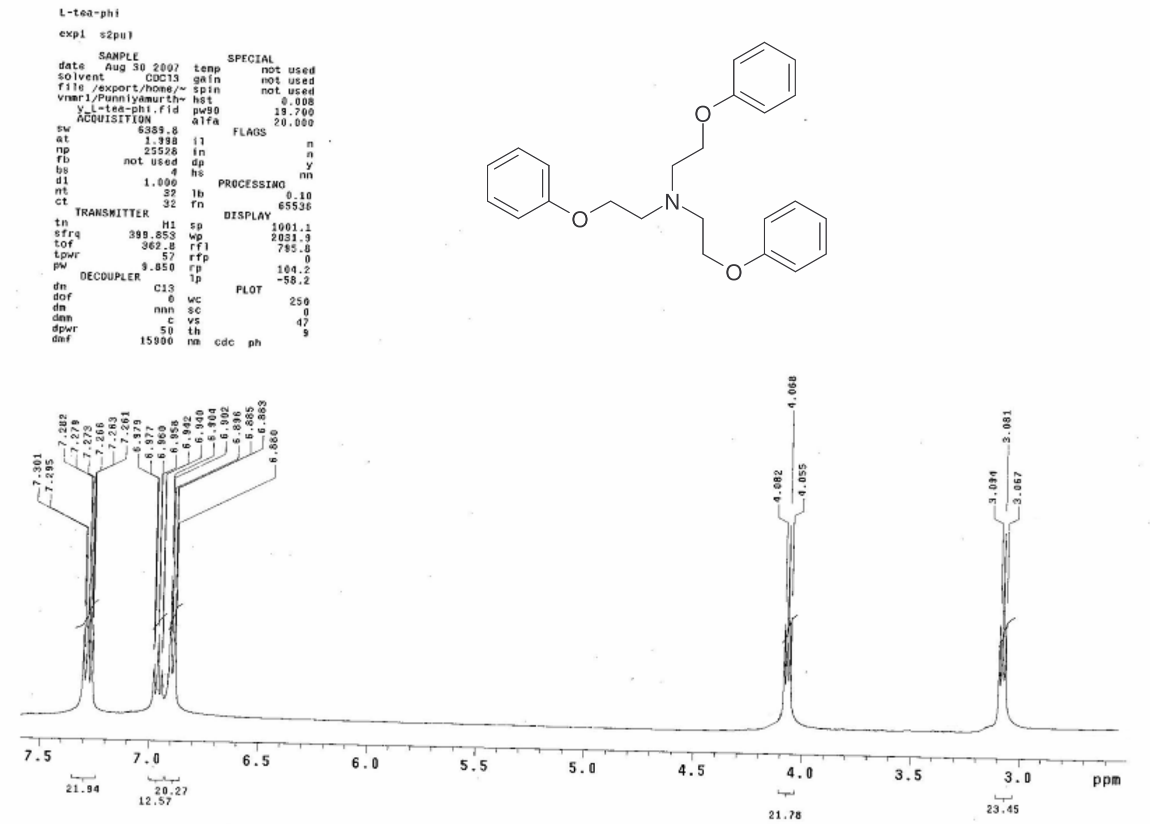

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   ACQUISITION       alfa            20.000
sw           6389.8           FLAGS
at            1.998  il                   n
np            25528  in                   n
fb         not used  dp                   y
bs                4  hs                  nn
d1            1.000          PROCESSING
nt               32  lb                0.10
ct               32  fn               65536
   TRANSMITTER               DISPLAY
tn               H1  sp              1001.1
sfrq        399.853  wp              2031.9
tof           362.8  rfl              795.8
tpwr             57  rfp                  0
pw            9.850  rp               104.2
    DECOUPLER        lp               -58.2
dn              C13           PLOT
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dm              nnn  sc                   0
dmm               c  vs                  47
dpwr             50  th                   9
dmf           15900  nm   cdc   ph
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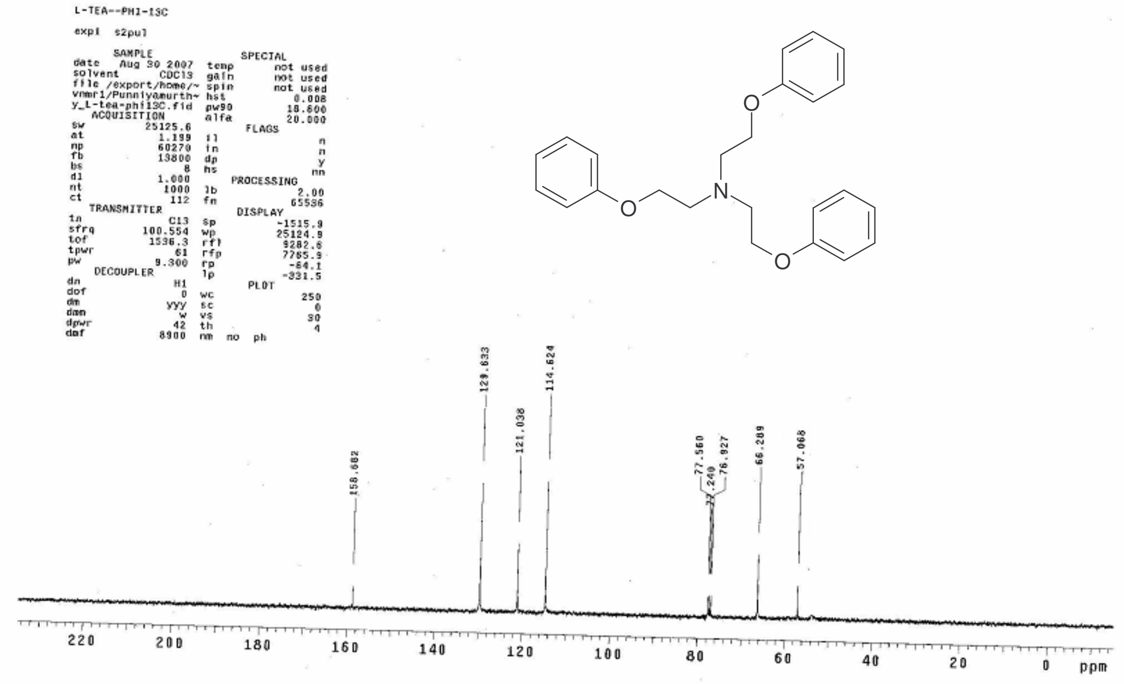

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   ACQUISITION       alfa            20.000
sw          25125.6           FLAGS
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np            60270  in                   n
fb            13800  dp                   y
bs                8  hs                  nn
d1            1.000          PROCESSING
nt             1000  lb                2.00
ct              112  fn               65536
   TRANSMITTER               DISPLAY
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sfrq        100.554  wp             25124.9
tof          1536.3  rfl             9282.6
tpwr             61  rfp             7765.9
pw            9.300  rp               -64.1
    DECOUPLER        lp              -331.5
dn               H1           PLOT
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dm              yyy  sc                   0
dmm               w  vs                  90
dpwr             42  th                   4
dmf            8900  nm   no   ph
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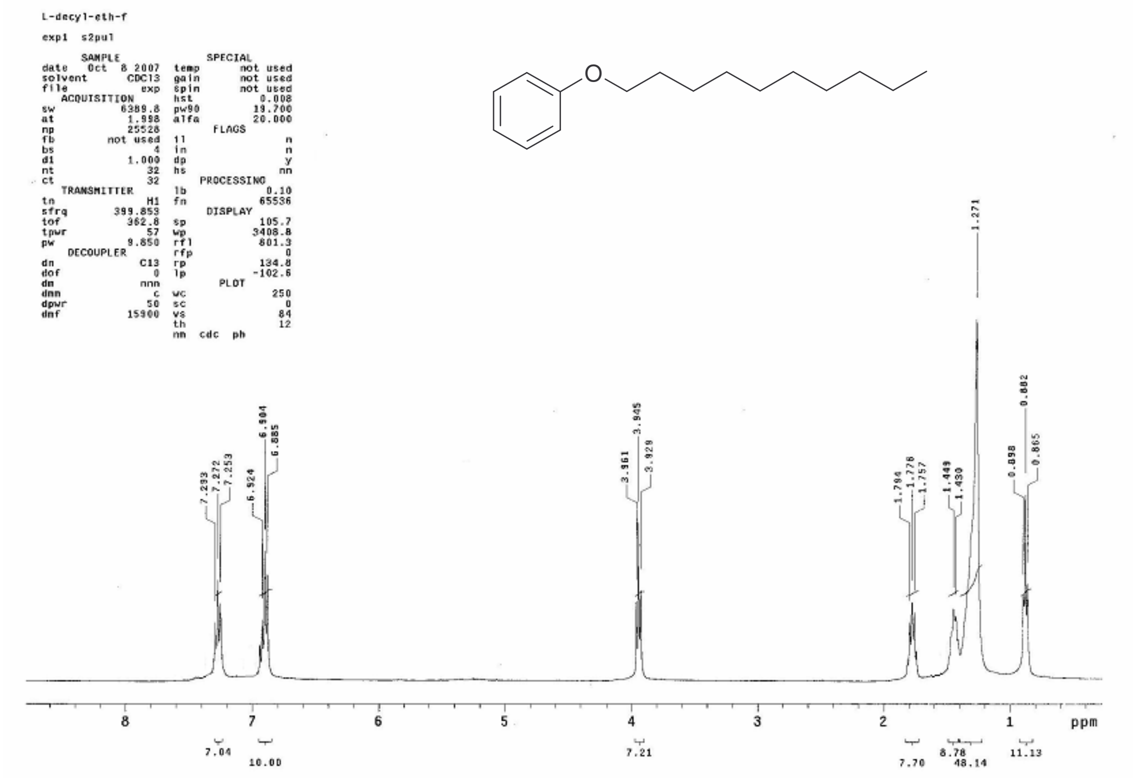

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L-decyl-eth-f

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file            exp   spin        not used
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at            1.998   alfa          20.000
np            25528            FLAGS
fb         not used   il                 n
bs                4   in                 n
d1            1.000   dp                 y
nt               32   hs                nn
ct               32          PROCESSING
   TRANSMITTER        lb              0.10
tn               H1   fn             65536
sfrq        399.853           DISPLAY
tof           362.8   sp             105.7
tpwr             57   wp            3408.8
pw            9.850   rfl            801.3
    DECOUPLER         rfp                0
dn              C13   rp             134.8
dof               0   lp            -102.6
dm              nnn             PLOT
dmm               c   wc               250
dpwr             50   sc                 0
dmf           15900   vs                84
                      th                12
                      nm  cdc  ph
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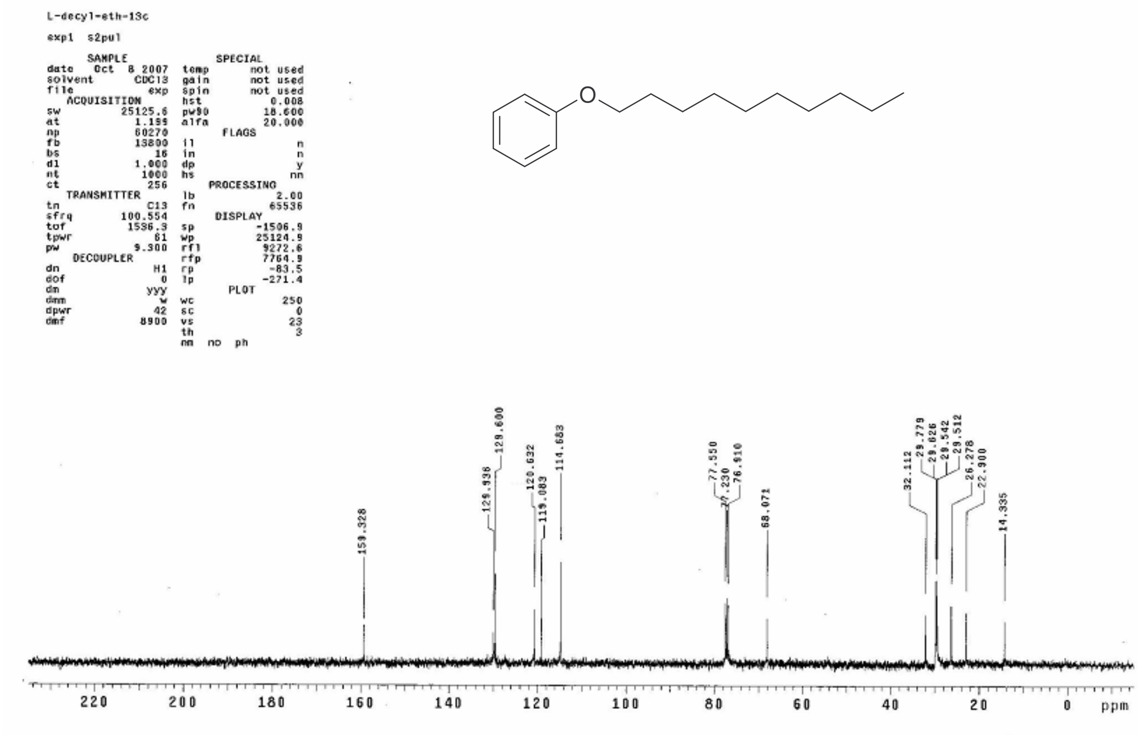

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L-decyl-eth-13c

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solvent       CDCl3   gain        not used
file            exp   spin        not used
   ACQUISITION        hst            0.008
sw          25125.6   pw90          18.600
at            1.199   alfa          20.000
np            60270            FLAGS
fb            13800   il                 n
bs               16   in                 n
d1            1.000   dp                 y
nt             1000   hs                nn
ct              256          PROCESSING
   TRANSMITTER        lb              2.00
tn              C13   fn             65536
sfrq        100.554           DISPLAY
tof          1536.3   sp           -1506.9
tpwr             61   wp           25124.9
pw            9.300   rfl           9272.6
    DECOUPLER         rfp           7764.9
dn               H1   rp             -83.5
dof               0   lp            -271.4
dm              yyy             PLOT
dmm               w   wc               250
dpwr             42   sc                 0
dmf            8900   vs                23
                      th                 3
                      nm  no  ph
```

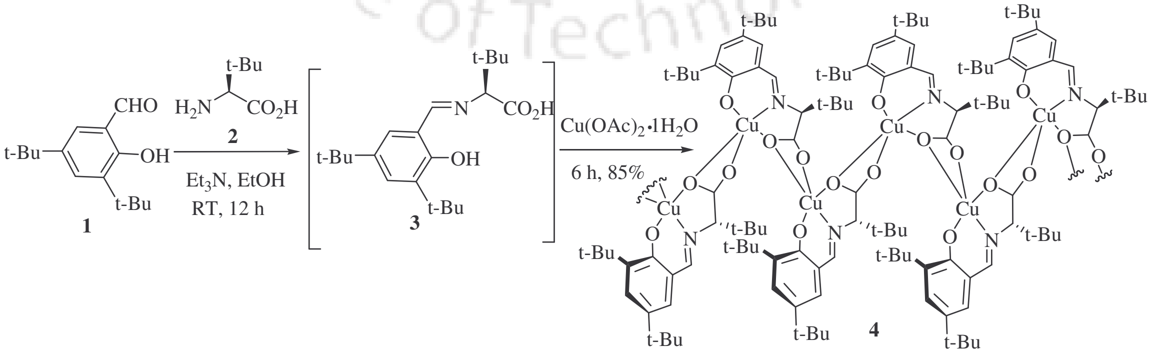
Chapter IV

Synthesis, Crystal Structure and Application of Chiral Copper(II) Coordination Polymer for Asymmetric Catalysis

The study of stereoregular chiral coordination polymers is a very active interdisciplinary research topic with potential applications in asymmetric catalysis, chiral sensor, nonlinear optical and chiral magnetic materials.[1-2] The building blocks approach includes the possibility of introducing chiral centers in either metal complexes or ligands to obtain chiral network.[3] Transition metal complexes of chiral Schiff base ligands having multifunctional coordination groups (carbonyl and carboxylate oxygen) could be good candidates to be used as metalloligands for constructing extended multi-dimensional chiral supramolecular coordination polymers.

Synthesis of Chiral Coordination Polymer

Reaction of the 3,5-di-*tert*-butylsalicylaldehyde **1** with L-*tert*-leucine **2** in the presence of Et_3N provided Schiff base **3** which was reacted *in situ* with $Cu(OAc)_2 \cdot 1H_2O$ to afford the polymer **4** as green colored crystals in 85 % yield (Scheme 1). Recrystallization of the polymer **4** in MeOH and CH_2Cl_2 gave single crystal whose X-ray analysis showed that it is stereoregular and the repeating units having O-H interaction are connected to each other by perpendicular fashion (Figure 1). The carboxylate group acts as a linker and copper(II) atoms are pentacoordinated with square pyramidal geometry.[4] The catalytic activity of **4** was then studied for asymmetric sulfoxidation with 30% H_2O_2, asymmetric desymmetrization of *meso*-epoxides with nitrogen nucleophiles and asymmetric benzoylation of secondary alcohols.



Scheme 1

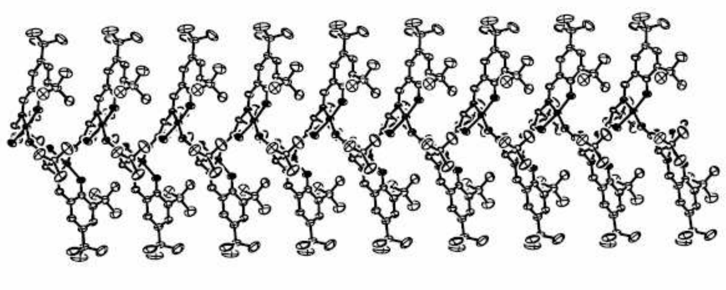
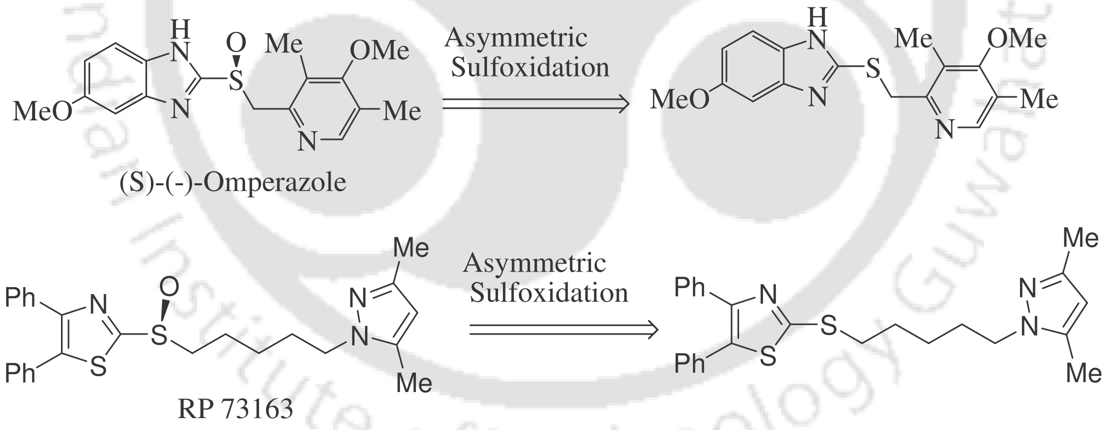


Figure 1. *ORTEP* Diagram of Coordination Polymer **4**. H-Atoms are Omitted for Clarity.

4.1 Asymmetric Sulfoxidation with Aqueous Hydrogen Peroxide

Optically active sulfoxides constitute a class of versatile chiral controllers and useful synthons in asymmetric synthesis, and they are of great interest in the pharmaceutical industry as biologically significant compounds (Scheme 2).[5] The synthesis of chiral non-racemic sulfoxides with high enantiomeric purity has been a subject of constant interest over the past two decades. In recent years growing research attention has been made for the preparation of these compounds by asymmetric catalysis.

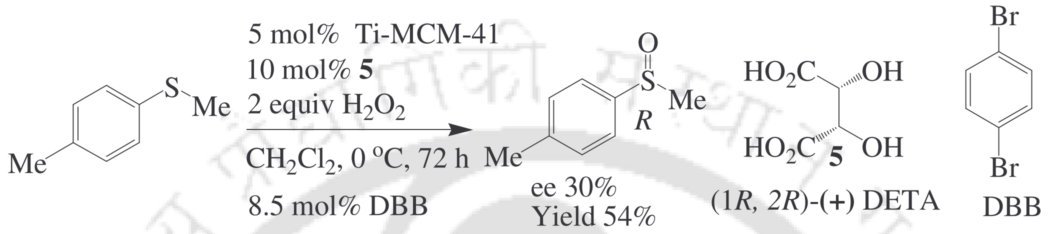


Scheme 2

The reactions employing chiral complexes of Ti, V, Fe and Mn have been found to be successful affording the sulfoxides in moderate to good enantioselectivity. These reactions have used variety of terminal oxidants such as *t*-butyl hydroperoxide,[6a] cumene hydroperoxide,[6b] urea hydrogen peroxide[6c] and iodosylbenzene.[6d] While the reactions with aqueous H_2O_2 are attractive since they generate water as only by-product. Further aqueous H_2O_2 is less expensive, atom efficient and safe to handle which make its use very attractive for "green" oxidation processes.

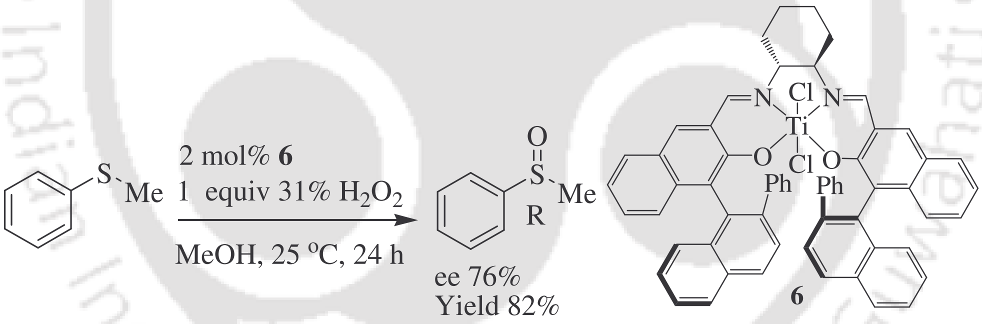
4.1.1 Titanium Catalysts

Asymmetric sulfoxidation of prochiral sulfides was first accomplished successfully by Kagan and co-workers in 1984 using *t*-butyl hydroperoxide as terminal oxidant by modified Sharpless method.[6a] After nearly a decade, Iwamoto and co-workers employed H_2O_2 for asymmetric sulfoxidation with up to 30% ee in the presence of Ti-containing mesoporous silica and optically active tartaric acid **5** (Scheme 3).[7a]



Scheme 3

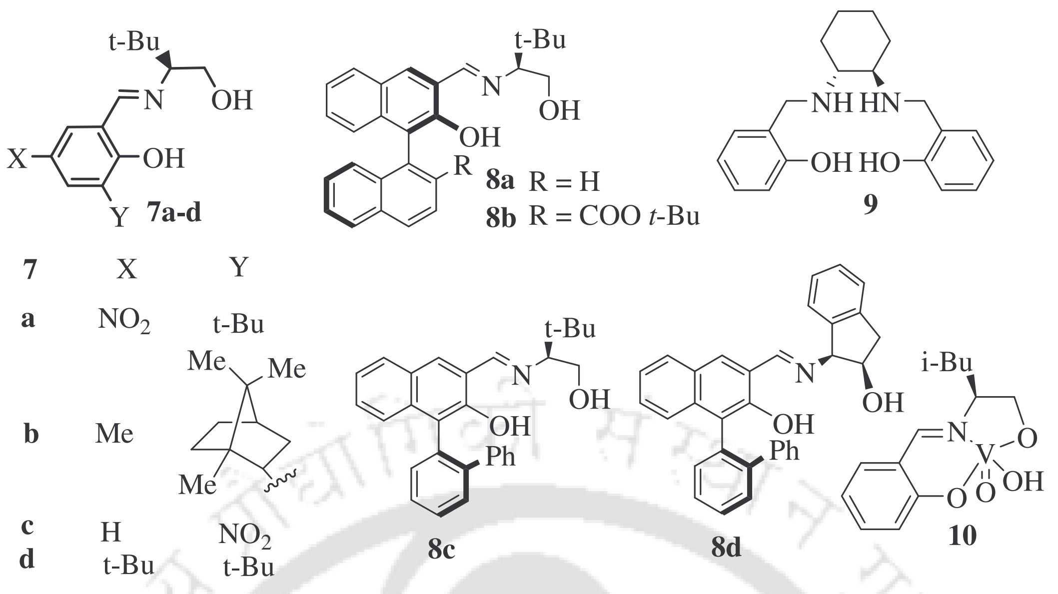
Di-μ-oxo titanium-salen **6** has been subsequently shown to catalyze the oxidation of aryl alkyl sulfides in the presence of 31% H_2O_2 at ambient temperature (Scheme 4).[6c] These reactions have provided the sulfoxides with up to 76% ee.



Scheme 4

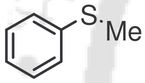
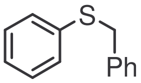
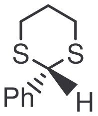
4.1.2 Vanadium Catalysts

Chiral vanadium based catalysts are widely studied for the oxidation of alkyl aryl sulfides with aqueous H_2O_2. The chiral ligands **7-9** and catalyst **10** employed for these reactions are summarized in Scheme 5.[8] The vanadium catalyzed systems are more effective compared to the titanium catalyzed processes.



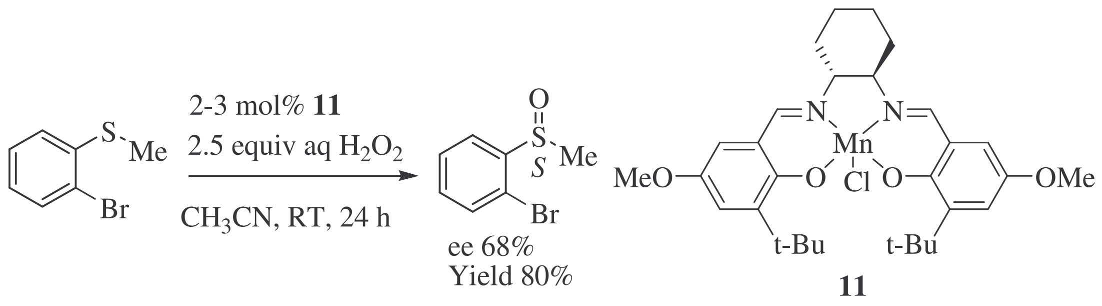
Scheme 5

Table 1. Vanadium Catalyzed Asymmetric Sulfoxidation with Aqueous H_2O_2

Entry	Sulfide	Catalyst	Ligand	Solvent	Temp.(°C)	Yield (%)	ee (%)	Ref.
1		$VO(acac)_2$	**7a**	CH_2Cl_2	0	77	88	8a
2		$VO(acac)_2$	**7b**	CH_2Cl_2	RT	88	50	8b
3		$VO(acac)_2$	**7c**	CH_2Cl_2	0	91	70	8c
4		$VO(acac)_2$	**8a**	CH_2Cl_2	RT	92	78	8a
5		$VO(acac)_2$	**8b**	CH_2Cl_2	RT	90	86	8d
6		$VO(acac)_2$	**8c**	CH_2Cl_2	RT	71	83	8a
7		$VO(acac)_2$	**8d**	CH_2Cl_2	0	81	88	8a
8		$VO(acac)_2$	**9**	$CHCl_3$	0	78	72	8e
9		**10**	-	CH_2Cl_2	RT	59	86	8f
10		$VO(acac)_2$	**7d**	CH_2Cl_2	RT	84	85	8g

4.1.3 Manganese Catalyst

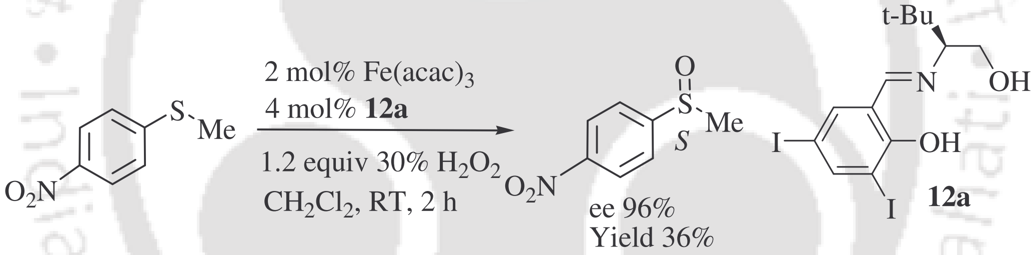
After the success with asymmetric epoxidation, chiral Mn-salen complexes are studied for asymmetric sulfoxidation of aryl alkyl sulfides (Scheme 6).[9] The reactions with aqueous H_2O_2 are examined in CH_3CN at ambient temperature with moderate to good enantioselectivity.



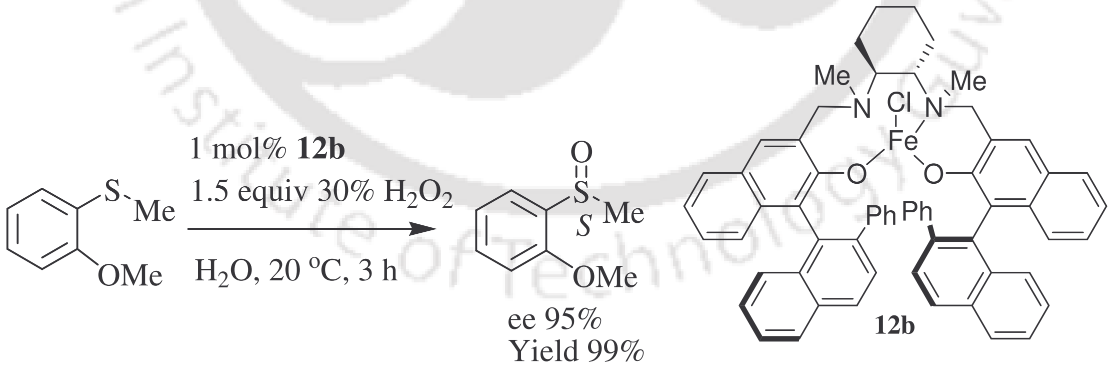
Scheme 6

4.1.4 Iron Catalysts

Few studies are focused on the iron catalyzed asymmetric oxidation of aryl alkyl sulfides with aqueous H_2O_2 at ambient temperature.[10] These studies are attractive from environmental and economic view point. Bolm and Legros showed the oxidation of aryl alkyl sulfides employing ligand **12a** with $Fe(acac)_3$ in the presence of 30% H_2O_2 in excellent enantioselectivity (Scheme 7).[10a] The addition of aromatic carboxylic acids as additive enhances the enantioselectivity of the reactions.



Scheme 7

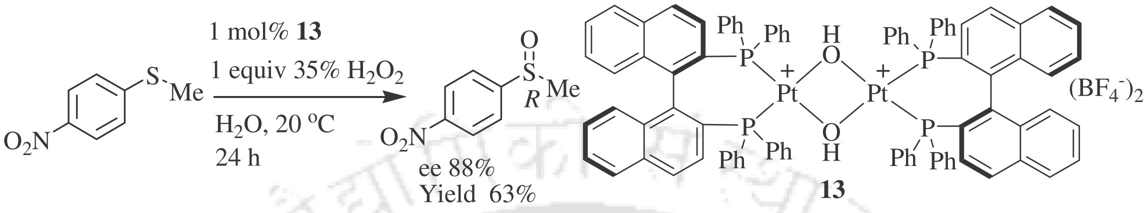


Scheme 8

Katsuki and Egami reported the asymmetric oxidation of aryl alkyl sulfides using chiral iron-salan complex **12b** with 30% H_2O_2 in water (Scheme 8).[10b] These reactions are efficient catalyzing the oxidation of variety of aryl alkyl sulfides with excellent enantioselectivity with high turnovers.

4.1.5 Platinum Catalyst

Chiral platinum complex, $\{[(R)\text{-BINAP}]\text{Pt}(\text{m-OH})\}_2(\text{BF}_4)_2$ **13**, is employed for the oxidation of aryl alkyl sulfides with 35% H_2O_2 in the presence of sodium dodecyl sulfate (SDS) surfactant in water (Scheme 9).[11] The reactions are efficient affording the sulfoxides with high enantioselectivity and excellent turnovers.

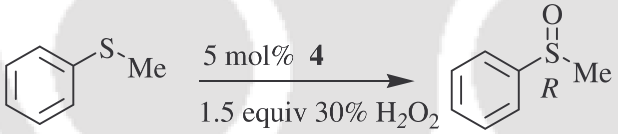


Scheme 9

4.2 Present Study

The polymer **4** was studied for the oxidation of aryl alkyl sulfides with 30% aqueous H_2O_2 at ambient temperature. Methyl phenyl sulfide was studied as a standard substrate to optimize the reaction conditions (Table 2). The reaction occurred to afford the desired methyl phenyl sulfoxide in good yield and 12% ee.

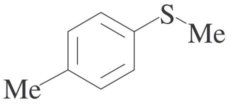
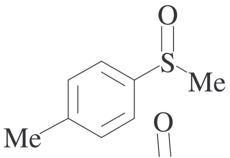
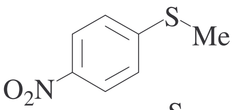
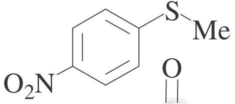
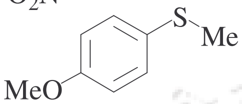
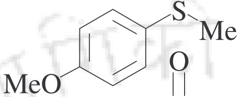
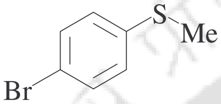
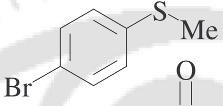
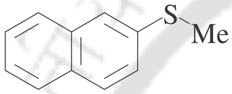
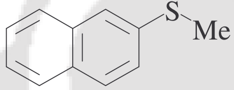
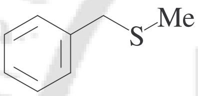
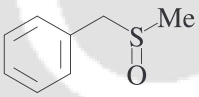
Table 2. Chiral Sulfoxidation using Complex Polymer **4** with 30% H_2O_2



Entry	Temp. (°C)	Solvent	Time (h)	Yield (%)[a]	er (%)[b]	Config.
1	25	CH_2Cl_2	15	88	51:49	*R*
2	25	CH_2Cl_2	12	73	50:50[c]	*R*
3	25	CH_2Cl_2	18	40	50:50[d]	*R*
4	0	CH_2Cl_2	23	70	53:47	*R*
5	0	CH_3CN	25	55	55:45	*R*
6	0	$(CH_3)_2CO$	26	45	50:50	*R*
7	-10	CH_2Cl_2	25	67	56:44	*R*

[a] Substrate (1 mmol), complex **4** (5 mol%) and 30% H_2O_2 (1.5 mmol) were stirred in solvent (3 mL). [b] Determined by chiral HPLC with OB-H column using 80:20 hexane:isopropanol.
[c] *t*-BuOOH used, [d] *m*-CPBA used.

Table 3. Chiral Copper(II) **4** Catalyzed Asymmetric Sulfoxidation with 30% H_2O_2

Entry	Sulfide	Product	Time (h)	Yield (%)[a]	er (%)	Config.[b]
1			28	70	55:4[c]	*R*
2			42	45	52:48[d]	*R*
3			24	80	56:44[c]	*R*
4			28	50	59:41[e]	*R*
5			26	50	57:43[d]	*R*
6			21	45	57:43[c]	*R*

[a] Substrate (1 mmol), catalyst **4** (5 mol%) and 30% H_2O_2 (1.5 mmol) were stirred at -10 ^{0}C in CH_2Cl_2 (3 mL).

[b] Determined by comparing the sign of optical rotation with literature.

Determined by chiral HPLC using hexane: isopropanol.

[c] OB-H column.

[d] AD column.

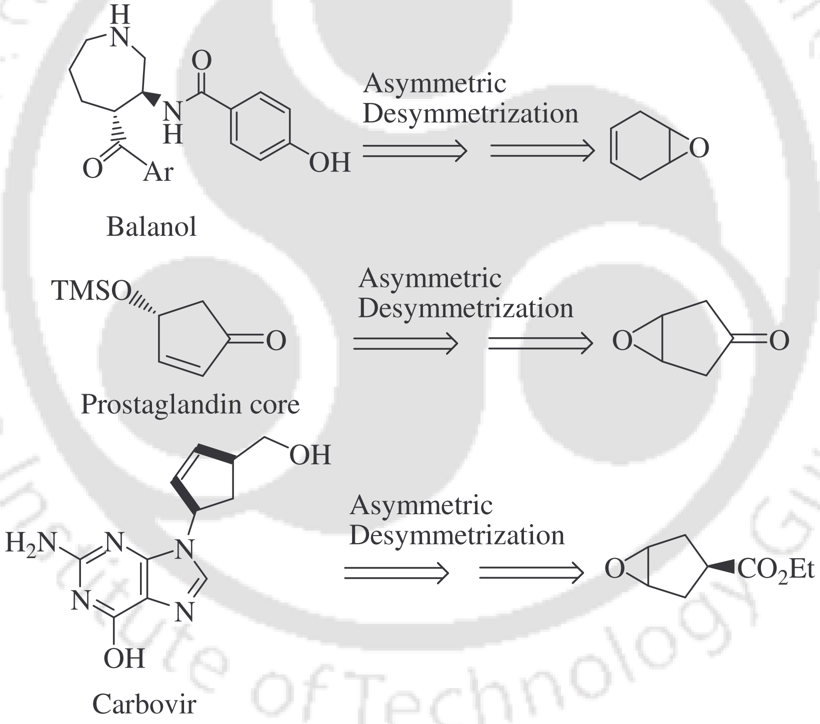
[e] OD column.

Among the solvents studied, CH_2Cl_2, CH_3CN, $(CH_3)_2CO$ and toluene, the former provided the best results. The optimum temperature was found to be -10 ^{o}C. Further lowering of the temperature did not show any enhancement with enantioselectivity. TBHP and *m*-CPBA were also employed as terminal oxidants, but those reactions provided racemic products. To study the scope of the procedure, the reaction of other alkyl aryl sulfides next studied (Table 3). *p*-Anisyl methyl sulfide, methyl naphthyl sulfide and methyl tolyl sulfide were oxidized up to 13% ee. Methyl 4-nitrophenyl sulfide underwent oxidation with 16% ee and the reaction of 4-bromophenyl methyl sulfide gave 17% ee. The reactions were selective (>99%) providing the sulfoxides as the sole products without over oxidation to sulfones.

In summary, the oxidation of methyl aryl sulfides are studied using copper(II) polymer **4** in the presence of 30% H_2O_2. The reactions occurred to afford the sulfoxides with good yields and enantioselectivity up to 17% ee.

4.3 Asymmetric Desymmetrization of *meso*-Epoxides

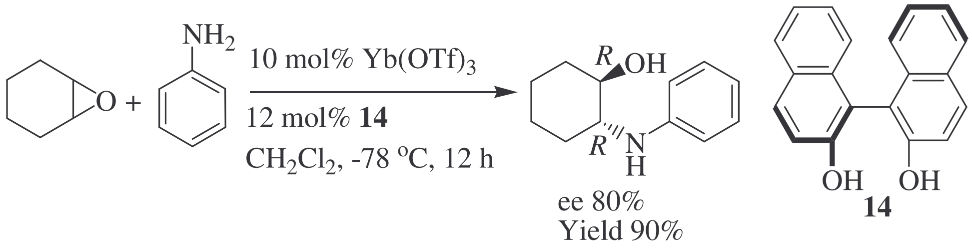
Optically active β-amino alcohols are versatile chiral building blocks in organic synthesis (Scheme 10).[5] Asymmetric desymmetrization of *meso*-epoxides with amines using chiral catalysts constitutes one of the effective methods for the synthesis of these molecules. Thus, chiral Lewis acid catalysts are considerably studied for the opening of cyclic epoxides with aryl amines. These reactions are found to be successful affording the amino alcohols with moderate to high enantioselectivity.



Scheme 10

4.3.1 Ytterbium Catalyst

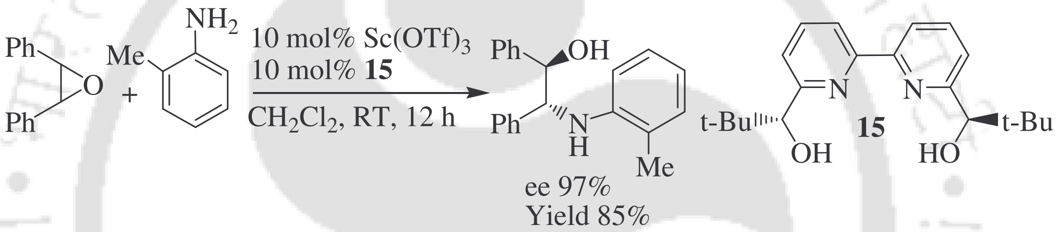
The reaction of *meso*-epoxides with aryl amines is studied by the combined use of $Yb(OTf)_3$ and *R*-BINOL **14** at -78 ^{o}C in CH_2Cl_2 (Scheme 11).[12] Both cyclic and acyclic epoxides are studied with aniline bearing electron donating substituents as nucleophiles with good enantioselectivity.



Scheme 11

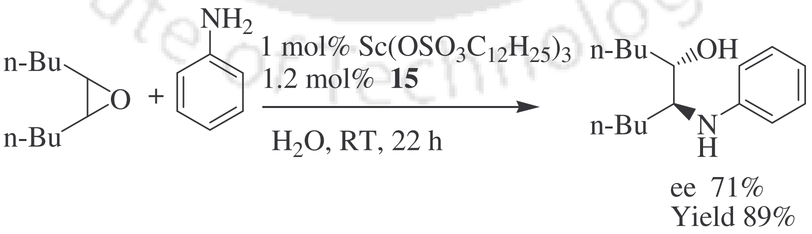
4.3.2 Scandium Catalysts

Few studies are focused on the use of $Sc(OTf)_3$ with ligand **15** for the reaction of *meso*-epoxides with amines at ambient temperature. Schneider and co-workers used $Sc(OTf)_3$ with **15** to afford the amino alcohols in high enantioselectivity (Scheme 12).[13a] These reaction conditions are also suitable for the reaction of *meso*-epoxides with oxygen nucleophiles.



Scheme 12

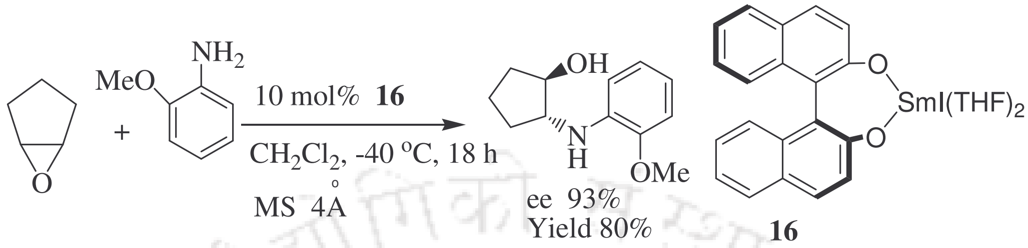
Kobayashi and co-workers employed $[Sc(OSO_3C_{12}H_{25})_3]$ and ligand **15** for the reaction of *meso*-epoxides with amines in water (Scheme 13).[13b] The water medium showed enhanced enantioselectivity compared to that in CH_2Cl_2. These reaction conditions are also suitable for the reaction of epoxides with *N*-containing heterocyclic compounds.



Scheme 13

4.3.3 Samarium Catalyst

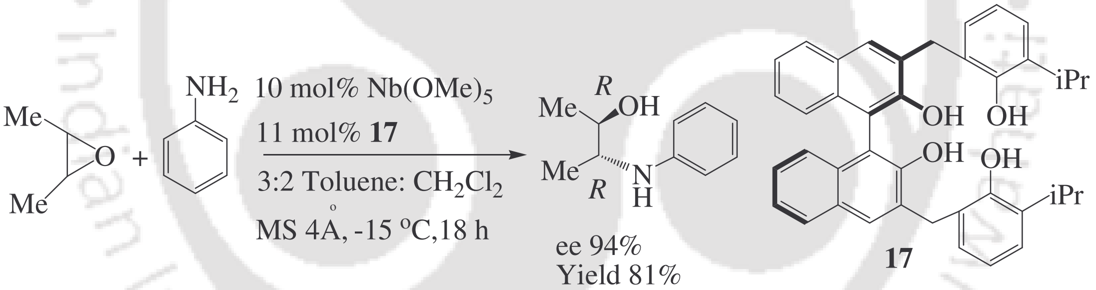
Chiral samarium complex **16** is studied for the opening *meso*-cyclic epoxides with aryl amines. These reactions are studied at -40 ° C in CH_2Cl_2 with up to 93% ee (Scheme 14).[14]



Scheme 14

4.3.4 Niobium Catalyst

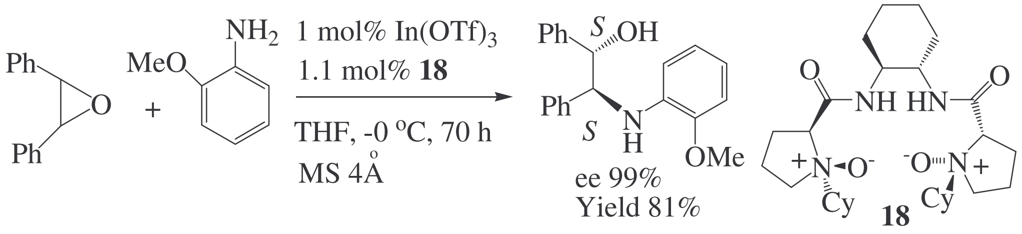
Kobayashi and co-workers showed the opening of *meso*-epoxides with amines by the combined use of $Nb(OMe)_5$ and ligand **17** in a mixture of toluene and CH_2Cl_2 (Scheme 15).[15] The reaction of acyclic epoxides exhibited high enantioselectivity compared to that with cyclic epoxides.



Scheme 15

4.3.5 Indium Catalyst

Feng and co-workers reported the opening of *meso*-epoxides with aryl amines employing $In(OTf)_3$ and ligand **18** in THF (Scheme 16).[16] A variety of epoxides and amines are studied with moderate to high enantioselectivity.

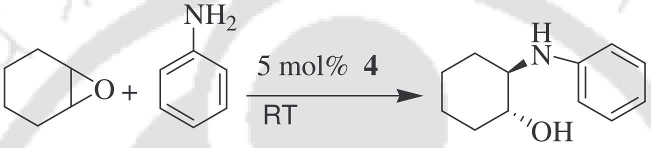


Scheme 16

4.4 Present Study

The chiral coordination polymer **4** was studied for the opening cyclic *meso*-epoxides with aryl amines. The reaction of cyclohexene oxide was first studied with aniline to optimize the reaction conditions (Table 4). As anticipated the reaction occurred to afford the desired 2-phenylamino-1-cyclohexanol with 12% ee. The reaction was efficient at ambient temperature in 1:1 mixture of water and THF compared to that CH_2Cl_2, CH_3CN, DMF, THF, toluene and water.

Table 4. Desymmetrization of Cyclohexene Oxide with Aniline



Entry	Solvent	Time (h)	Yield (%)[a]	ee (%)[b]	Config.[c]
1	CH_2Cl_2	14	80	5	*R,R*
2	CH_3CN	16	70	6	*R,R*
3	DMF	16	65	4	*R,R*
4	Toluene	18	98	7	*R,R*
5	THF	18	68	8	*R,R*
6	H_2O :THF(1:1)	18	75	10	*R,R*

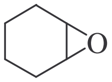
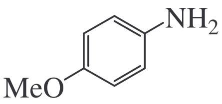
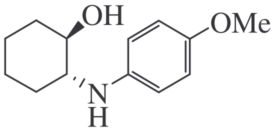
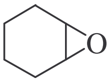
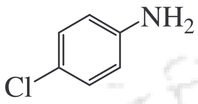
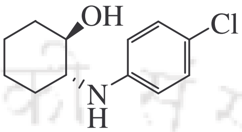
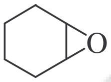
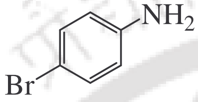
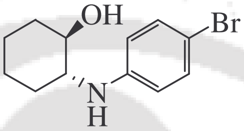
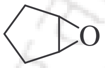
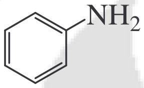
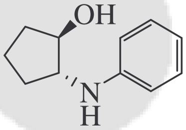
[a] Epoxide (1 mmol), aniline (1 mmol) and catalyst **4** (5 mol%) were stirred in solvent (1 mL) at ambient temperature.

[b] Determined by chiral HPLC using OD-H column with hexane:isoporpanol (85:15).

[c] Determined by comparing the sign of optical rotation with literature data.

Next, we studied the reaction of other nucleophiles with cyclohexene oxide. The reaction of cyclohexene oxide with *p*-anisidine provided the corresponding 1,2-β–amino alchol in 14% ee. Similar results were observed with 4-chloroaniline and 4-bromoaniline affording the respective amino alcohols in 20% and 25% ee, respectively. While the reaction of *meso*-cyclopentene oxide with aniline provided corresponding aminoalcohol in 18% ee.

Table 5. Application of **4** for Desymmetrisation of *meso*-Epoxides with Amines.

Entry	Epoxide	Amine	Product	Yield (%)[a]	ee (%)	Config.[b]
1				55	14[c]	*1R, 2R*
2				58	20[d]	*1R, 2R*
3				60	25[d]	*1R, 2R*
4				65	18 [e]	*1R, 2R*

[a] Substrate (1 mmol), complex **4** (5 mol%) and amine were stirred in 1:1 THF: water (3 mL) at ambient temperature.

[b] Determined by comparing the sign of optical rotation with literature data.

Determined by chiral HPLC using hexane and isopropanol as eluent

[c] OD-H column.

[d] OD column.

[e] AD column.

In summary, the desymmetrisation of *meso*-cyclic epoxides studied with aniline derivatives using catalyst **4** with good yields and enantioselectivity up to 25% ee.

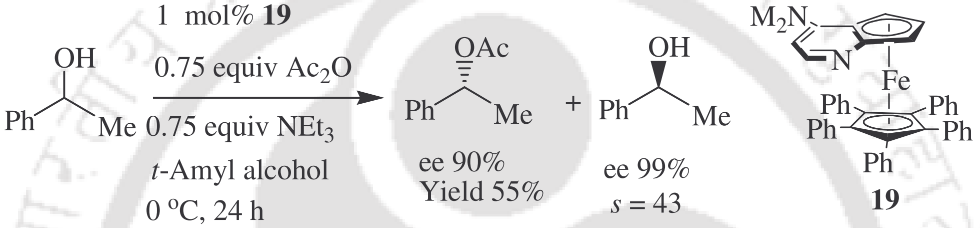
4.5 Asymmetric Benzoylation of Secondary Alcohols

Kinetic resolution of alcohols is a fundamental and one of the effective methods to avail optically active alcohols (Scheme 17).[17] In recent years, number of non-enzymatic chiral catalysts are developed which, in some cases, exhibit practically useful levels of enantioselectivity. Chiral enantioselective acyl transfer provides a convenient method for kinetic resolution of racemic alcohols and desymmetrization of *meso*-diols.

Scheme 17

4.5.1 Planar-Chiral Heterocycle Catalyst

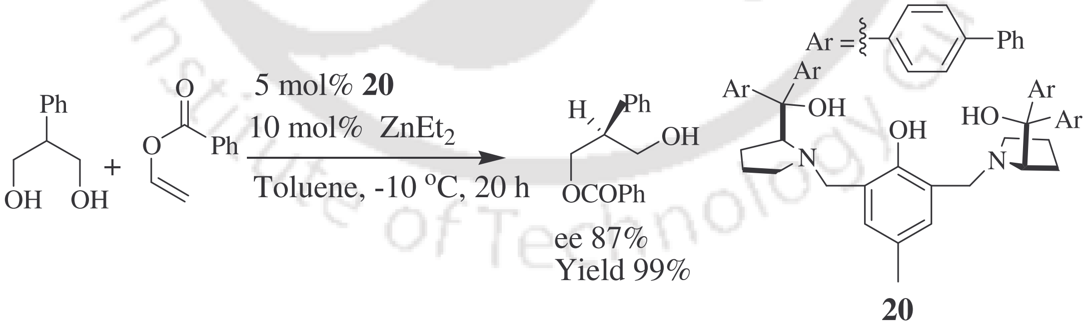
Fu and co-workers demonstrated the kinetic resolution of secondary alcohols using planar chiral DMAP derivatives **19** as nucleophilic catalysts (Scheme 18).[18] Allyl and aryl alcohols undergo reactions with high enantioselectivity.



Scheme 18

4.5.2 Zinc Catalyst

Trost and Mino employed binuclear zinc catalyst derived from $ZnEt_2$ and ligand **20** for the resolution of 1,3-diols with high enantioselectivity (Scheme 19).[19] The reaction is suitable with electron donating phenyl rings and hetero aromatic rings.



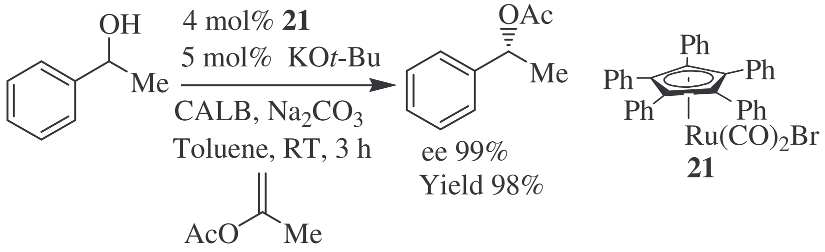
20

Scheme 19

4.5.3 Ruthenium Catalyst

Ruthenium complex **21** in combination with Candida antarctica lipase B (CALB) is used for the resolution of secondary alcohols in presence of isopropenyl acetate (Scheme 20).[20]

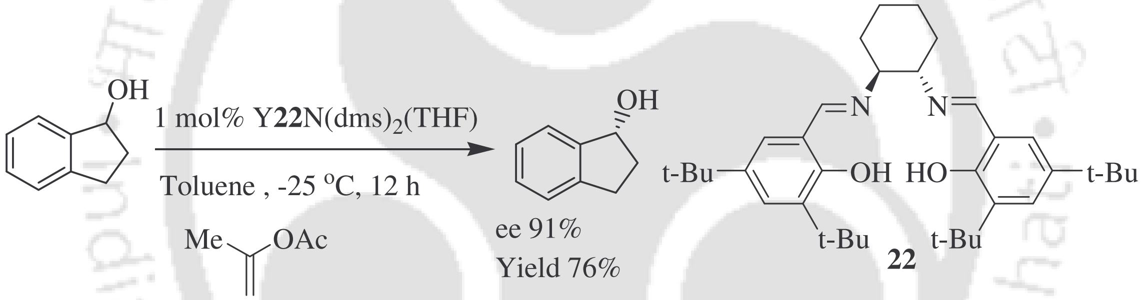
Phenyl ethanol having electron donating and -withdrawing group is resolved in high enantioselectivity.



Scheme 20

4.5.4 Yttrium Catalyst

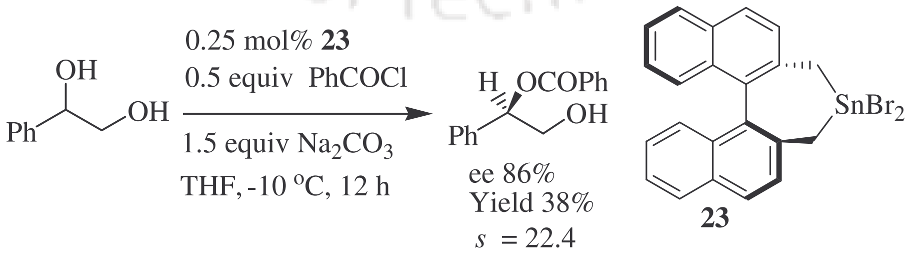
Yttrium-dimethyl sulfide-THF in combination with salen ligand **22** is used for the kinetic resolution of secondary alcohols with the above described acylating agent. Under these conditions, indanol is resolved with 91% ee (Scheme 21).[21]



Scheme 21

4.5.5 Tin Catalyst

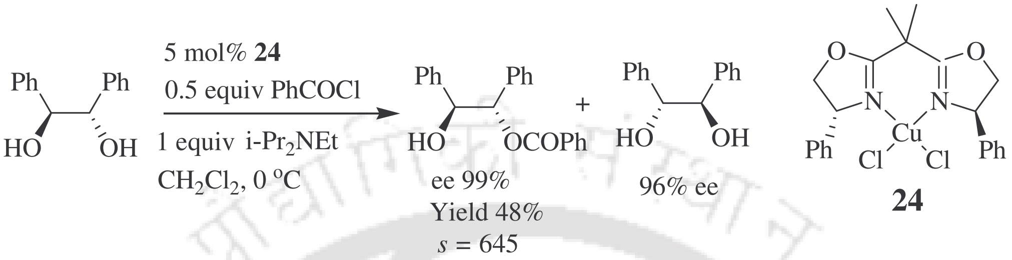
Matsumura and co-workers employed chiral tin complex **23** for monobenzoylation of acyclic vicinal diols (Scheme 22).[22] Reactions are occurred to afford the desired benzoylated product with up to 86% ee.



Scheme 22

4.5.6 Copper(II) Catalysts

Few studies focused on the use of copper (II) bisoxazoline based catalysts for monobenzoylation of 1,2-diols with benzoyl chloride in the presence of tertiary amines (Scheme 23).[23] The reactions are occurred efficiently to afford the monobenzoylated product with excellent enantioselectivity.



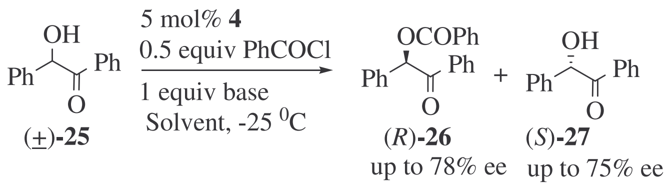
Scheme 23

4.6 Present Study

The catalytic activity of the polymer **4** was studied for asymmetric benzoylation of secondary alcohols. The reaction of benzoin **25** was studied as a standard substrate to optimize the reaction conditions (Table 6). The reaction occurred to afford desired benzoylated product with 62% ee when the reaction was allowed to stir with 5 mol% of **4** (with respect to the repeating unit) and 0.5 equiv of benzoyl chloride in the presence of Et$_3$N at 0 °C. The reaction in THF showed the highest enantioselectivity (62%) compared to that CH$_2$Cl$_2$ (42% ee), acetone (60% ee) and toluene (41% ee). No reaction was observed in solvents such as DMF and CH$_3$CN. Further reduction of the reaction temperature to -25 °C showed enhancement in the enantioselectivity to 78% with selectivity s = 13.8. The unreacted benzoin showed 75% ee. The reaction of *trans*-1,2-(±)-diols **28a-b** was next studied (Table 7). Cyclohexanediol **28a** underwent reaction to give monobenzoylated product **29a** in 62% ee. Similarly, hydrobenzoin **28b** underwent reaction to afford the monobenzoylated product in 50% ee. The unreacted 1,2-diols showed 56% ee and 44% ee, respectively.

To reveal the nature of the polymer **4** in solution, MALDI TOF MS of **4** in CHCl$_3$ was studied. Peaks corresponding to dimer, trimer, tetramer and pentamer were observed suggesting that the polymer undergoes dissociation into oligomers in solution. Thus, these oligomers may be dissociated into monomers during the reaction process and catalyze the reaction (Scheme 24). Reaction of the oligomers with 1,2-diol may give the

Table 6. Asymmetric Benzoylation of Benzoin using Polymer **4**



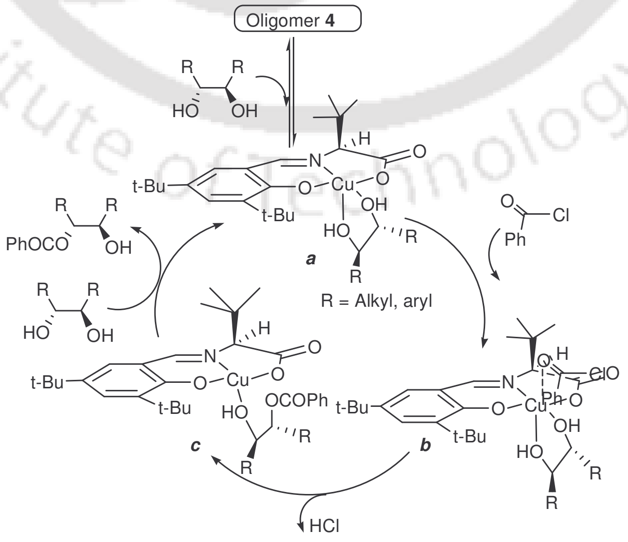
Entry	Solvent	Base	Temperature (°C)	Time(h)	**26** (ee %)[b]	Conversion (%)[d]	**27** (ee %)[c]	s[d]	Config.
1	CH_2Cl_2	Et_3N	0	4.5	42	45	35	3.4	*R*
2	Acetone	Et_3N	0	4.5	60	48	56	6.9	*R*
3	Toluene	Et_3N	0	4.5	41	48	38	3.4	*R*
4	Et_2O	Et_3N	0	4.5	25	33	17	1.9	*R*
5	THF	Et_3N	0	4.5	62	46	53	9.9	*R*
6	THF	Et_3N	-10	6.5	65	47	58	8.3	*R*
7	THF	Et_3N	-25	8	78	49	75	18	*R*
8	THF	$^iPr_2NH$	-25	22	43	45	35	3.5	*R*
9	THF	Pyridine	-25	25	0	-	-	-	-
10	THF	2,6-Lutidine	-25	25	35	41	25	2.6	*R*

[a] Substrate (1 mmol), catalyst **4** (5 mol% with respect to repeating unit), benzoyl chloride (0.5 mmol) and Et_3N (1 mmol) were subjected to the appropriate conditions.

[b] Determined by HPLC analysis using chiralcel OD-H column with hexane and isopropanol (19:1) as eluent.

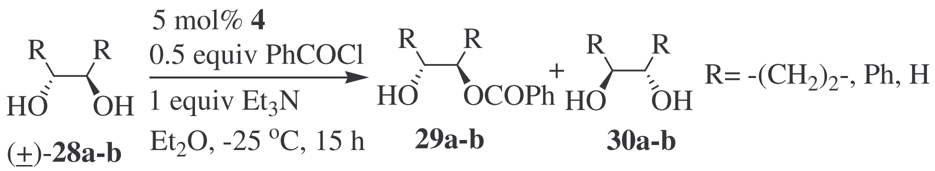
[c] Determined from the sign of optical rotation.

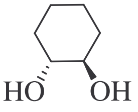
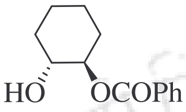
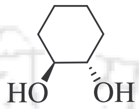
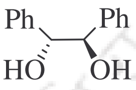
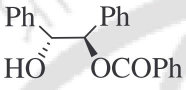
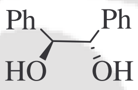
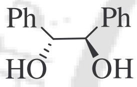
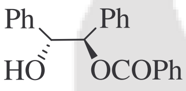
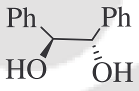
[d] Determined according to ref 23b.



Scheme 24

Table 7. Monobenzoylation of (±)-*trans*-1,2-Diols using Polymer **4**



Entry	(±)-28a-b	29a-b[a]	ee(%)[b]	30a-b	ee(%)[c]	Conv(%)[d]	*s*[d]	Config.[e]
1	 (±)-**28a**	 **29b**	62	 **30a**	56	47	12.3	*1R,2R*
2	 (±)-**28b**	 **29b**	50	 **30b**	44	47	7.2	*1R,2R*
3	 (±)-**28b**	 **29b**	26[f]	 **30b**	20	26	2.0	*1R,2R*

[a] Substrate (1 mmol), polymer **4** (5 mol% with respect to repeating unit), benzoyl chloride (0.5 mmol) and Et_3N (1 mmol) were stirred at -25 °C for 15 h in THF.

[b] Determined by HPLC using chiralcel OJ column with hexane and isopropanol as eluent.

[c] Determined by HPLC using chiralcel OD-H column with hexane and isopropanol as eluent.

[d] Determined according to ref 23b.

[e] Determined from the sign of optical rotation.

[f] K_2CO_3 used.

monomeric complex ***a*** that could react with the acylating agent to give intermediate ***b***. The latter ***b*** could be transformed to intermediate ***c*** by intramolecular acylation of the OH group with acylating agent. The intermediate ***c*** can complete the catalytic cycle by replacing the acylated product with fresh 1,2-diol.

In summary, the synthesis, crystal structure and application of chiral copper(II) coordination polymer **4** for asymmetric benzoylation of secondary alcohols is accomplished with 78% ee. The polymer **4** can be obtained by single step in high yield.

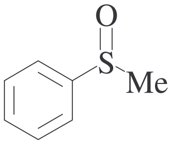
Experimental Section

General. Sulfides, epoxides, alcohols and L-*tert*-leucine (99%) were obtained from Aldrich. Optical rotation was measured using Perkin Elmer-343 polarimeter. UV-vis spectrum was recorded from Perkin Elmer Lambda 25 spectrometer. TGA was performed using Mettler Toledo TGA/SDTA 851 thermogravimetric analyzer. EPR spectrum was recorded using JES-FA200 ESR spectrometer. MALDI-TOF-MS spectrum was recorded by Micro Mass TofSpec 2E using nitrogen 337 nm laser. Magnetic susceptibility data were measured by Lokshore 8200 with oscillator frequency = 330 Hz, time constant = 1 sec and voltage sensitivity = 10 mill volt. HPLC analysis was carried out on Waters 2478 with chiral stationary phase columns (Chiralcel OJ, OB-H and OD-H).

Preparation of Polymer 4: Aldehyde **1** (3 mmol, 702 mg), L-*tert*-leucine (3 mmol, 393.5 mg) and Et_3N (3 mmol, 303 mg) were stirred in EtOH (10 mL) at room temperature for 12 h. The resultant yellow solution having **3** was treated with $Cu(OAc)_2{\cdot}1H_2O$ (3 mmol, 598 mg) and the stirring was continued for an additional 6 h. The solvent was evaporated and the residue was purified on silica gel flash column chromatography using CH_2Cl_2 and methanol (19:1) as eluent to afford **4** as green colored crystals. Yield 85% (1.057 g); $[\alpha]_D^{25}$ + 718 (c = 0.026, CH_2Cl_2); UV/vis (CH_2Cl_2) λ_{max} (ε) = 600 (2250), 392 (10546), 282 nm (29038 $mol^{-1}dm^3cm^{-1}$); EPR (X-band, MeOH, liquid N_2), $g_{\perp} = 2.040$, $g_{\parallel} = 2.291$, $A_{\parallel} = 283.11$ G; IR (KBr): ν 2960, 1619, 1585, 1466, 1439, 1379, 1205, 1168, 1096, 1035, 840, 789, 595, 549, 415 cm^{-1}. Anal Calcd for $(C_{21}H_{31}CuNO_3)_n$: C 72.05; H 8.92; N 4.32. Found: C 72.20; H 8.78; N 4.35. MS MALDI/TOF: 2025. **Crystal Data For 4**: $C_{21}H_{31}CuNO_3$, Mw = 409.06, orthorhombic; $P2_12_12_1$; $a = 6.2168(7)$ Å, $b = 16.4734(18)$ Å, $c = 21.668(2)$ Å; $\alpha = 90^0$, $\beta = 90^0$, $\gamma = 90^0$; $V = 2219.0(4)$ Å^3; $Z = 2$, $D_{calcd} = 1.224$ mgm^{-3}; $T = 296(2)$ K; Scan range $6.26^o < \theta < 28.32^o$; crystal dimension 0.50 x 0.16 x 0.10 mm^3; 5416 reflections, 4428 unique reflections; $(I > 2\sigma(I))$; $R_1 = 0.0360$; $wR_2 = 0.0785$ (all data); GOF (on F^2) = 1.016.

General Procedure for Sulfoxidation

The aryl methyl sulfide (1 mmol), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were stirred at -10 ^oC in CH_2Cl_2 (3 mL) under nitrogen atmosphere. The reaction mixture was then quenched with Na_2SO_3 (0.5 mmol). Drying (Na_2SO_4) and evaporation of the organic layer provided a residue, which was purified on silica gel column chromatography using ethyl acetate and hexane as eluent.



(*R*)-Methyl phenyl sulfoxide. Methyl phenyl sulfide (1 mmol, 124 mg), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to the reaction described in the general procedure to afford methyl phenyl sulfoxide with 67% (93 mg) yield as colorless liquid.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.67 (m, 2H), 7.55 (m, 3H), 2.73 (s, 3H).

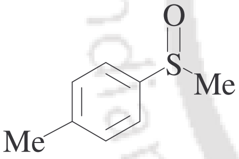
^{13}C NMR ($CDCl_3$, 100 MHz) δ 145.13, 130.45, 128.78, 122.90, 43.35.

IR (neat): ν 3065, 2985, 1085, 1040, 740, 690 cm^{-1}.

Anal Calcd for C_7H_8OS : C 59.97; H 5.75; S 22.87. Found: C 59.95; H 5.76; S 22.90.

HPLC: ee = 12%; Chiralcel OB-H column, eluent *n*-hexane/isopropanol (80/20), flow rate 0.8 mL/min.

$[\alpha]_D^{25}$ = +18 (c = 0.425, Acetone).



(*R*)-*p*-Tolyl methyl sulfoxide. *p*-Tolyl methyl sulfide (1 mmol, 138 mg), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to the reaction conditions described in the general procedure to give *p*-tolyl methyl sulfoxide in 70% (107 mg) yield as colorless solid.

Mp: 85-86 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.55 (d, *J* = 8.1 Hz, 2H), 7.34 (d, *J* = 8.4 Hz, 2H), 2.70 (s, 3H), 2.42 (s, 3H).

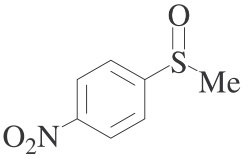
^{13}C NMR ($CDCl_3$, 100 MHz) δ 142.30, 129.90, 123.40, 44.00, 21.40.

IR (KBr): ν 3040, 2990, 1580, 1450, 1070, 1030, 820 cm^{-1}.

Anal Calcd for $C_8H_{10}OS$ **:** C 62.30; H 6.54; S 20.79. Found: C 62.34; H 6.58; S 20.80.

HPLC: ee = 10%; Chiralcel OB-H column, eluent *n*-hexane/isopropanol (50/50), flow rate 0.5 mL/min.

$[\alpha]_D^{25}$ = +14 (c = 0.633, Acetone).



(*R*)-Methyl *p*-nitrophenyl sulfoxide. Methyl- *p*-nitrophenyl sulfide (1 mmol, 169 mg), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to general procedure reaction conditions to provide methyl *p*-nitrophenyl sulfoxide in 45% (83 mg) yield as colorless solid

Mp: 150-152 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.52 (d, *J* = 8.1 Hz, 2H), 8.08 (d, *J* = 8.2 Hz, 2H), 2.55 (s, 3H).

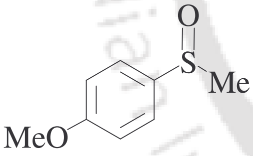
^{13}C NMR ($CDCl_3$, 100 MHz) δ 153.10, 149.30, 124.60, 124.40, 43.80.

IR (KBr): ν 3086, 2992, 2906, 1642, 1580, 1504, 1418, 1330, 1113, 1089, 964, 849, 828, 735, 676, 524, 464 cm^{-1}.

Anal Calcd for $C_7H_7NO_3S$: C 45.40; H 3.81; S 17.31; N 7.56. Found: C 45.46; H 3.82; S 17.36; N 7.60.

HPLC: ee = 16%; Chiralcel AD column, eluent *n*-hexane/isopropanol (94/6), flow rate 1.0 mL/min.

$[\alpha]_D^{25}$ = +11 (c = 1.32, Acetone).



(*R*)-*p*-Anisyl methyl sulfoxide. *p*-Anisyl methyl sulfide (1 mmol, 154 mg), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to the reaction conditions described in the general procedure to afford *p*-anisyl methyl sulfoxide in 80% (136 mg) yield as colorless oil.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.58 (d, *J* = 9 Hz, 2H), 7.08 (d, *J* = 9 Hz, 2H), 3.81 (s, 3H), 2.70 (s, 3H).

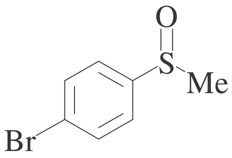
^{13}C NMR ($CDCl_3$, 100 MHz) δ 161.90, 136.50, 125.40, 114.80, 55.50, 43.90.

IR (neat): ν 3070, 1590, 1300, 1250, 1085, 1020 $cm^{-1.}$

Anal Calcd for $C_8H_{10}O_2S$ **:** C 56.44; H 5.92; S 18.84. Found: C 56.49; H 5.90; S 18.86.

HPLC: ee = 12%; Chiralcel OB-H column, eluent *n*-hexane/isopropanol (50/50), flow rate 0.5 mL/min.

$[\alpha]_D^{25}$ = +8 (c = 0.55, $CHCl_3$).



(*R*)-Methyl *p*-bromophenyl sulfoxide. Methyl *p*-bromophenyl sulfide (1 mmol, 201 mg), complex **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to the reaction conditions described in the general procedure to give (*R*)-methyl *p*-bromophenyl sulfoxide in 50% (108 mg) yield as colorless solid.

Mp: 87 ^oC.

^1H NMR ($CDCl_3$, 400 MHz) δ 7.67 (d, *J* = 8.7 Hz, 2H), 7.52 (d, *J* = 8.7 Hz, 2H), 2.72, (s, 3H).

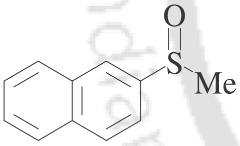
^{13}C NMR ($CDCl_3$, 100 MHz) δ 144.70, 132.40, 125.30, 125.00, 43.90.

IR (KBr): ν 2990, 2910, 1083, 1041, 815, 512 cm^{-1}.

Anal Calcd for C_7H_7OSBr : C 38.37; H 3.22; S 14.63. Found: C 38.40, H 3.29, S 14.68.

HPLC: ee = 17%; Chiralcel OD column, eluent *n*-hexane/isopropanol (99/1), flow rate 0.8 mL/min.

$[\alpha]_D^{25}$ = +18 (c = 0.24, Acetone).



(*R*)-2-Naphthyl methyl sulfoxide. 2-Naphthyl methyl sulfide (1 mmol, 174 mg), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to the reaction conditions described in the general procedure to afford 2-naphthyl methyl sulfoxide in 50% (95 mg) yield as colorless solid.

Mp: 97 ^oC.

^1H NMR ($CDCl_3$, 400 MHz) δ 8.21-7.87 (m, 5H), 7.70-7.40 (m, 2H), 2.58 (s, 3H).

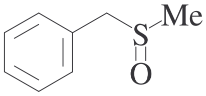
^{13}C NMR ($CDCl_3$, 100 MHz) δ 142.60, 134.30, 132.80, 129.50, 128.40, 128.00, 127.70, 127.30, 123.90, 119.30, 43.70.

IR (KBr): ν 3040, 1580, 1030, 820, 755 cm^{-1}.

Anal Calcd for $C_{11}H_{10}OS$: C 69.44; H 5.30; S 16.85. Found: C 69.50, H 5.32, S 16.91.

HPLC: ee = 14%; Chiralcel AD column, eluent *n*-hexane/isopropanol (95/5), flow rate 0.5 mL/min.

$[\alpha]_D^{25}$ = +18 (c = 1.9, Acetone).



(*R*)-Benzyl methyl sulfoxide. Benzyl methyl sulfide (1 mmol, 138 mg), polymer **4** (5 mol% with respect to monomer, 20 mg) and 30% H_2O_2 (1.5 mmol, 165 μL) were subjected to the reaction conditions described in the general procedure to give benzyl methyl sulfoxide in 45% yield (69 mg) as a colorless solid.

Mp: 51 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.45-7.21 (m, 5H), 4.06 (d, *J* =12.8 Hz, 1H), 3.93 (d, *J* =12.8 Hz, 1H), 2.45 (s, 3H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 128.90, 128.30, 127.50, 123.70, 58.60, 42.60.

IR (KBr): ν 3040, 1490, 1450, 1370, 1295, 1015 cm^{-1}

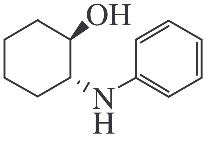
Anal Calcd for $C_8H_{10}SO$: C 62.3; H 6.53; S 20.79. Found: C 61.98; H 6.49; S 20.73.

HPLC: ee = 13%; Chiralcel OB-H column, eluent *n*-hexane/isopropanol (80/20), flow rate 0.5 mL/min.

$[\alpha]_D^{25}$ = +7 (c = 3, EtOH).

General Procedure for Asymmetric Desymmetrisation

To a stirred solution of polymer **4** (5 mol% with respect to repeating unit, 20 mg) and epoxide (1.2 mmol) in 1:1 THF and water (1 ml), was added aniline (1 mmol). The reaction mixture was stirred at ambient temperature and its progress was monitored by TLC. Evaporation of the solvent provided a residue that was dissolved in CH_2Cl_2 (10 mL) and washed with saturated $NaHCO_3$ (3 ml) and water (3 mL). Drying (Na_2SO_4) and evaporation of the solvent provided a residue that was purified on silica gel column chromatography using ethyl acetate and hexane as eluent.



(1*R*,2*R*)-2-Phenylamino-1-cyclohexanol. Aniline (1 mmol, 93 mg), cyclohexene oxide (1.2 mmol, 117 mg) and polymer **4** (5 mol% with respect to repeating unit, 20 mg) in 1:1 THF: H_2O (1 mL) were subjected to the reaction condition described in the general procedure to afford (1*R*,2*R*)-2-phenylamino-1-cyclohexanol as white solid in 65% (124 mg) yield.

Mp: 77–80 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.23-7.14 (m, 2H), 6.74-6.68 (m, 3H), 3.34-3.31 (m, 1H), 3.14 (m, 3H), 2.12–2.10 (m, 2H), 1.78–1.73 (m, 2H), 1.41–1.24 (m, 3H), 1.03 (m, 1H).

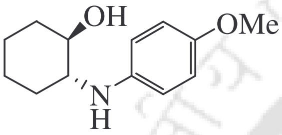
^{13}C NMR ($CDCl_3$, 100 MHz) δ 147.58, 129.18, 118.32, 114.30, 74.58, 60.17, 33.24, 31.78, 25.17, 24.39.

IR (KBr): ν 3677, 3390, 3049, 2931, 2856, 1600, 1502, 1448, 1068, 748 cm$^{-1.}$

Anal Calcd for $C_{12}H_{17}NO$: C, 75.35; H, 8.96; N, 7.32. Found: C, 75.40; H, 8.95; N, 7.38.

HPLC: ee = 10%; Chiralcel OD-H column, eluent *n*-hexane/isopropanol (85/15), flow rate 1.0 mL/ min.

$[\alpha]_D^{25}$ = -9 (c = 0.4, $CHCl_3$).



(1*R*,2*R*)-2-(4-Methoxyphenyl)amino-1-cyclohexanol. *p*-Anisidine (1 mmol, 123 mg), cyclohexene oxide (1.2 mmol, 117 mg) and polymer **4** (5 mol% with respect to repeating unit, 20 mg) in 1:1 THF: H_2O (1 mL) were subjected to the reaction condition described in the general procedure to afford (1*R*,2*R*)-2-(4-methoxyphenyl)amino-1-cyclohexanol as white solid in 55% yield (121 mg).

Mp: 64 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 6.85–6.72 (m, 2H), 6.70–6.65 (m, 2H), 3.78 (s, 3H), 3.45–3.30 (m, 1H), 3.20-2.90 (m, 3H), 2.20-2.05 (m, 2H), 1.90–1.65 (m, 2H), 1.50-1.20 (m, 3H), 1.10-0.95 (m, 1H).

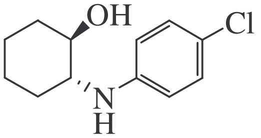
^{13}C NMR ($CDCl_3$, 100 MHz) δ 152.82, 141.55, 116.30, 114.77, 74.34, 61.60, 55.69, 33.02, 31.47, 25.04, 24.24.

IR (KBr)**:** ν 3677, 3529, 3366, 3021, 3013, 2938, 2861, 2836, 1612, 1512, 1465, 1450, 1401, 1296, 1239, 1221, 1180, 1136, 1067, 1038 cm^{-1}.

Anal Calcd for $C_{13}H_{19}NO_2$: C, 70.56; H, 8.65; N, 6.33. Found: C, 70.60; H, 8.67; N, 6.41.

HPLC: ee = 14%; Chiralcel OD-H column, eluent *n*-hexane/isopropanol (85/15), flow rate 1.0 mL/ min.

$[\alpha]_D^{25}$ = -11 (c = 0.9, $CHCl_3$).



(1*R*,2*R*)-2-(4-Chlorophenyl)amino-1-cyclohexanol. 4-Chloroaniline (1 mmol, 127 mg), cyclohexene oxide (1.2 mmol, 117 mg) and polymer **4** (5 mol% with respect to repeating unit, 20 mg) in 1:1 THF: H_2O (1 mL) were subjected to the reaction condition described in the general procedure to give (1*R*,2*R*)-2-(4-chlorophenyl)amino-1-cyclohexanol as white solid in 58% (130 mg) yield.

Mp: 101–103 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.17 (d, J = 5.29 Hz, 2H), 6.54 (d, J = 5.20 Hz, 2H), 3.32 (m, 1H), 3.03 (m, 1H), 2.85 (m, 2H), 2.03 (m, 2H), 1.67 (m, 2H), 1.27 (m, 3H), 1.03 (m, 1H).

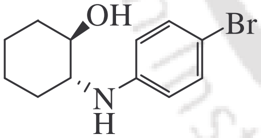
^{13}C NMR ($CDCl_3$, 400 MHz) δ 147.59, 129.15, 118.26, 114.30, 60.16, 33.26, 31.73, 29.77, 25.14, 24.38.

IR (KBr)**:** ν 3416, 3388, 3322, 2934, 2861, 1871, 1597, 1509, 1451, 1324, 1260 cm^{-1}.

Anal Calcd for $C_{12}H_{16}ClNO$: C, 63.85; H, 7.14; N, 6.21. Found: C, 63.96; H, 7.15; N, 6.30.

HPLC: ee = 20%; Chiralcel OD column, eluent *n*-hexane/isopropanol (85/15), flow rate 1.0 mL/ min.

$[\alpha]_D^{25}$ = -14 (c = 0.6, CH_2Cl_2).



(1*R*,2*R*)-2-(4-Bromophenyl)amino-1-cyclohexanol. 4-Bromoaniline (1 mmol, 172 mg), cyclohexene oxide (1.2 mmol, 117 mg) and polymer **4** (5 mol% with respect to repeating unit, 20 mg) in 1:1 THF:H_2O (1 mL) were subjected to the reaction conditions described in the general procedure to provide (1*R*, 2*R*)-2-(4-bromophenyl)amino-1-cyclohexanol as a colorless solid in 55% (161 mg) yield.

Mp: 121–123 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.24 (d, J = 8.16 Hz, 2H), 6.58 (d, J = 8.56 Hz, 2H), 3.35 (m, 1H), 3.06 (m, 1H), 2.12 (m, 3H), 1.77 (m, 2H), 1.35 (m, 4H), 1.04 (m, 1H).

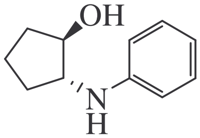
^{13}C NMR ($CDCl_3$, 100 MHz) δ 146.34, 131.88, 116.03, 74.44, 60.40, 33.36, 31.50, 25.01, 24.33.

IR (KBr): ν 3508, 3410, 3378, 3285, 2984, 2860, 1591, 1510, 1487, 1450, 1402, 1324, 1259, 1070 cm^{-1}.

Anal Calcd for $C_{12}H_{16}BrNO$: C, 53.35; H, 5.97; N, 5.18. Found: C, 53.41; H, 5.99; N, 5.22.

HPLC: ee = 25%; Chiralcel OD column, eluent *n*-hexane/isopropanol (85/15), flow rate 1.0 mL/ min.

$[\alpha]_D^{25}$ = -14 (c = 1.0, CH_2Cl_2).



(1*R*,2*R*)-2-Phenylamino-1-cyclopentanol. Aniline (1 mmol, 93 mg), cyclopentene oxide (1.2 mmol, 100 mg) and polymer **4** (5 mol% with respect to repeating unit, 20 mg) in 1:1 THF: H_2O (1 mL) were subjected to the reaction conditions described in the general procedure to afford (1*R*,2*R*)-2-phenylamino-1-cyclohexanol as white needles in 65% (115 mg) yield.

Mp: 56–58 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.19–7.15 (m, 2H), 6.73–6.65 (m, 3H), 4.07 (m, 1H), 3.61 (m, 1H), 2.98 (s, 2H), 2.33-2.32 (m, 1H), 2.03-1.94 (m, 1H), 1.88–1.65 (m, 3H), 1.45–1.36 (m, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 147.47, 129.12, 117.49, 113.31, 76.68, 62.12, 33.62, 32.88, 31.21, 21.09.

IR (KBr): ν 3613, 3429, 3055, 3022, 3012, 2965, 1603, 1505, 1430, 1315, 1261, 1103, 1075 cm^{-1}.

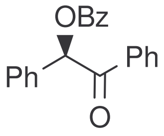
Anal Calcd for $C_{11}H_{15}NO$: C, 74.54; H, 8.53; N, 7.90. Found: C, 74.58; H, 8.52; N, 7.95.

HPLC: ee = 18%; Chiralcel AD column, eluent *n*-hexane/isopropanol (95/5), flow rate 0.8 mL/ min.

$[\alpha]_D^{25}$ = -2 (c = 0.54, $CHCl_3$).

General Procedure for Asymmetric Benzoylation

To a stirred solution of alcohol (1 mmol), polymer **4** (5 mol% with respect to monomeric unit, 20 mg) and Et_3N (1 mmol, 101 mg) in THF (2 mL), benzoyl chloride (0.5 mmol, 70 mg) was added. The mixture was stirred at -25 ^{o}C under nitrogen atmosphere until the benzoyl chloride disappeared (TLC). The reaction mixture was then treated with water and the solvent was evaporated. The residue was dissolved in CH_2Cl_2 (10 mL) and washed with Na_2HCO_3 (3 mL) and water (3 mL). Drying (Na_2SO_4) and evaporation of the solvent gave residue that was purified on silica gel column chromatography using ethyl acetate and hexane as eluent.



(*R*)-Benzoic acid 2-oxo-1,2-diphenyl-ethyl ester. Benzoin (1 mmol, 212 mg), polymer **4** (5 mol% with respect to monomeric unit, 20 mg), benzoyl chloride (0.5 mmol, 70 mg) and Et_3N (1 mmol, 101 mg) in THF were subjected to the reaction conditions described in the general procedure to afford the (*R*)-benzoic acid 2-oxo-1,2-diphenyl-ethyl ester as colorless solid.

Mp: 116-117 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.12-8.09 (m, 2H), 7.98-7.96 (m, 2H), 7.57-7.34 (m, 11H), 7.07 (s, 1H).

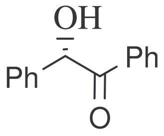
^{13}C NMR ($CDCl_3$, 100 MHz) δ 193.94, 166.26, 134.89, 133.94, 133.71, 133.57, 130.38, 130.19, 129.52, 129.34, 129.05, 128.88, 128.66, 128.61, 78.14.

IR (KBr): ν 3420, 2959, 2925, 1716, 1690, 1598, 1356, 1279, 1247, 1177, 1232, 957, 762, 696 cm^{-1}.

Anal Calcd for $C_{21}H_{16}O_3$: C 79.73, H 5.10. Found: C 79.74; H 5.11.

HPLC: ee = 78%; Chiralcel OD-H column, eluent *n*-hexane/isopropanol (19/1), flow rate 0.7 mL/min.

$[\alpha]_D^{25} = -176$ (c = 1.0, Acetone).



(*S*)-2-Hydroxy-1,2-diphenylethanone.

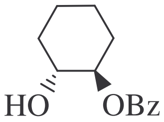
Mp: 133°C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.33-7.13 (m, 10H), 6.11 (m, 1H), 4.87 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 199.0, 139.0, 133.5, 129.1, 129.0, 128.7, 128.6, 127.8, 76.2.

HPLC: ee = 75%; Chiralcel OD column, eluent *n*-hexane/isopropanol (95/5), flow rate 0.4 mL/min.

$[\alpha]_D^{25} = +93$ (c = 1.0, Acetone).



(*R,R*)-Benzoic acid 2-hydroxy-cyclohexyl ester.

Trans-Cyclohexan-1,2-diol (1 mmol, 116 mg), polymer **4** (5 mol% with respect to monomeric unit, 20 mg), benzoyl chloride (0.5 mmol, 70 mg) and Et_3N (1 mmol, 101 mg) were subjected to the reaction conditions described in the general procedure for 15 h to give (*R,R*)-benzoic acid 2-hydroxy-cyclohexyl ester as colorless solid.

Mp: 93-94 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.04-7.98 (d, *J* = 9.0 Hz, 2 H), 7.57-7.49 (m, 1 H), 7.45-7.36 (m, 2 H), 4.86-4.75 (m, 2 H), 3.78-3.64 (m, 1 H), 2.21-2.02 (m, 2 H), 1.77-1.67 (m, 2 H), 1.50-1.20 (m, 4 H).

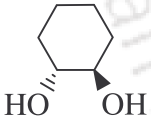
^{13}C NMR ($CDCl_3$, 100 MHz) δ 166.96, 133.26, 130.50, 129.86, 128.57, 78.91, 73.01, 33.18, 30.20, 24.09, 23.92.

IR (KBr): ν 2939, 2862, 1718, 1603, 1453, 1281 $cm^{-1.}$

Anal Calcd for $C_{21}H_{16}O_3$: C 70.79; H 7.32. Found: C 70.85; H 7.31.

HPLC: ee = 62%; Chiralcel OJ column, eluent *n*-hexane/isopropanol (97/3), flow rate 1.0 mL/min.

$[\alpha]_D^{25}$ = -50.5 (c = 1.37, MeOH).



(*S,S*)-Cylohexane-1,2 diol.

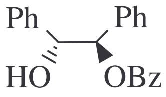
Mp: 108 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.32 (t, *J* = 3.6 Hz, 2H), 2.96 (s, 2H),1.93 (t, *J* = 3.2 Hz, 2H), 1.66 (t, *J* = 3.6 Hz, 2H), 1.23 (m, 4H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 75.97, 33.07, 24.54.

The product was monobenzoylated with benzoyl chloride in the presence of Et_3N and DMAP in CH_2Cl_2 at ambient temperature. Whose HPLC: ee = 56%; Chiralcel OJ column, eluent *n*-hexane/isopropanol (97/3), flow rate 1.0 mL/min.

$[\alpha]_D^{25}$ = +44.63 (c = 1.37, MeOH).



(*R,R*)-Benzoic acid 2-hydroxy-1,2-diphenyl-ethyl ester. 1,2-Diphenyl ethane-1,2-diol (1 mmol, 214 mg), polymer **4** (5 mol% with respect to monomeric unit, 20 mg), benzoyl chloride (0.5 mmol, 70 mg) and Et_3N (1 mmol, 101 mg) in THF were subjected to the reaction conditions described in the general procedure for 15 h to give (*R,R*)-Benzoic acid 2-hydroxy-1,2-diphenyl-ethyl ester as colorless solid.

Mp:147-148 °C.

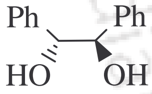
^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.13-8.10 (m, 2H), 7.62-7.55 (m, 1 H), 7.51-7.44 (m, 2 H), 7.30-7.16 (m, 10 H), 6.11 (d, *J* = 7.4 Hz, 1H), 5.10 (d, *J* = 7.4 Hz, 1 H), 2.73-2.56 (s, 1H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 165.78, 138.99, 136.79, 133.29, 129.98, 129.77, 128.52, 128.31, 128.26, 128.19, 127.29, 127.16, 80.60, 77.31.

IR (KBr): ν 3472, 3034, 1721, 1453, 1273, 1113, 704 $cm^{-1.}$

HPLC: ee = 50%; Chiralcel OJ column, eluent *n*-hexane/isopropanol (9/1), flow rate 1.0 mL/ min.

$[\alpha]_D^{25}$ = -48 (c = 1.37, MeOH).



(*S,S*)-1,2-Diphenyl ethane-1,2-diol.

Mp:142-144 °C.

^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.22-7.09 (m, 10H), 4.69 (s, 2H), 2.73 (s, 2H).

^{13}C NMR ($CDCl_3$, 100 MHz) δ 139.8, 128.1, 127.9, 126.9, 79.1.

HPLC: ee = 44%; Chiralcel OJ column, eluent *n*-hexane/isopropanol (9/1), flow rate 1.0 mL/min.

$[\alpha]_D^{25}$ = +42 (c = 1.0, $CHCl_3$).

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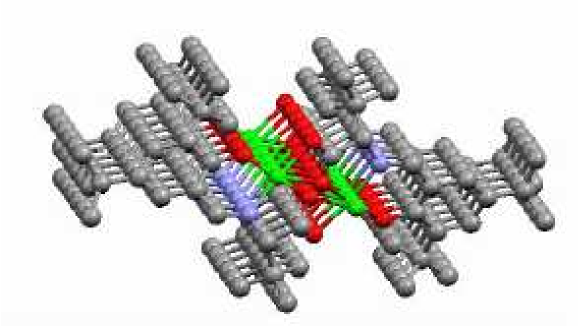


Figure 2. Parallel stacking of the polymer **4**

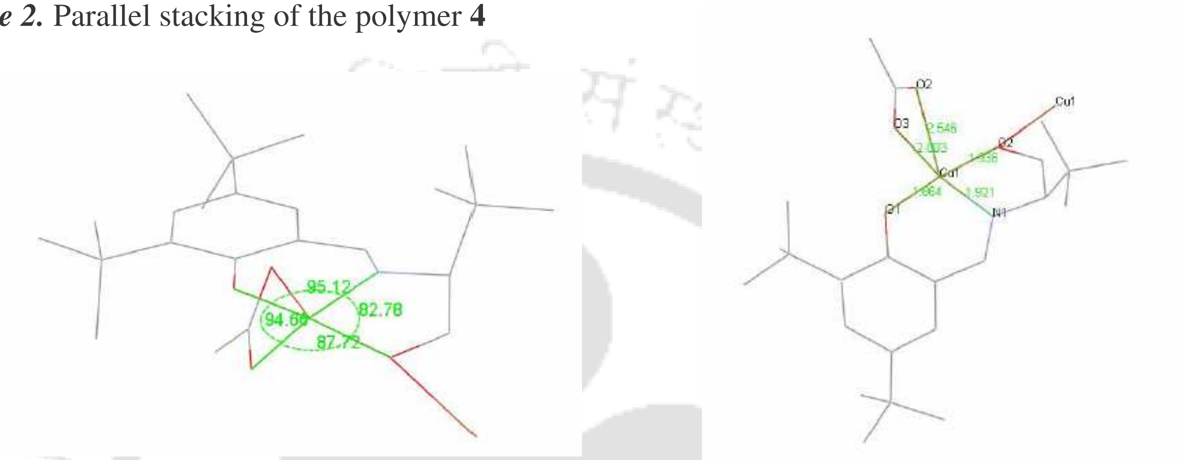


Figure 3. Wire frame of the polymer **4** showing bond angles and bond lengths. H-Atoms are omitted for clarity

O1- Cu1 - N1	95.12	O1 - Cu1 - O2	171.88	N1 - Cu1- O3	170.13
O1 - Cu1 - O3	94.66	N1 - Cu1 - O2	82.78	O2 - Cu1 - O3	87.72

N1-C10	1.289	N1-C12	1.470	O3-Cu1	2.003	Cu1-O1	1.865
N1-Cu1	1.921	O1-C1	1.319	Cu1-N1	1.921	Cu1-O2	1.936
O1-Cu1	1.865	O2-C24	1.267	Cu1-O3	2.003		
O2-Cu1	1.936	O3-C24	1.243				

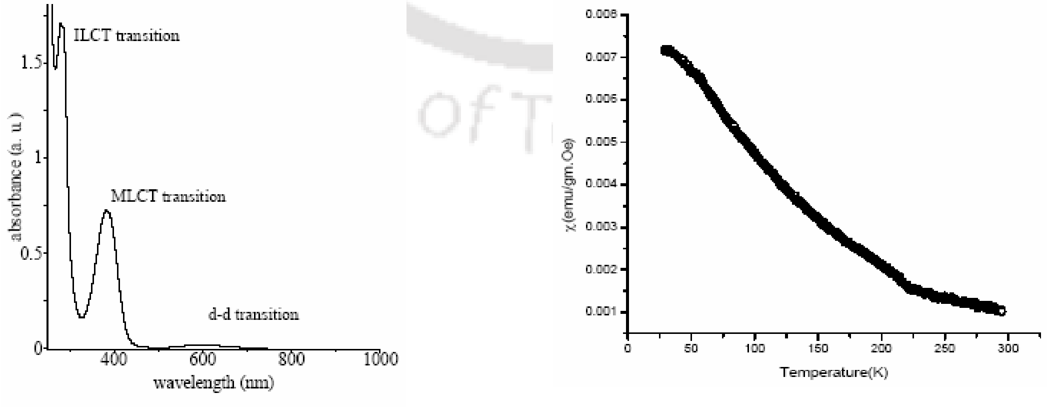


Figure 3. UV-visible spectra and magnetic susceptibility of of polymer **4**

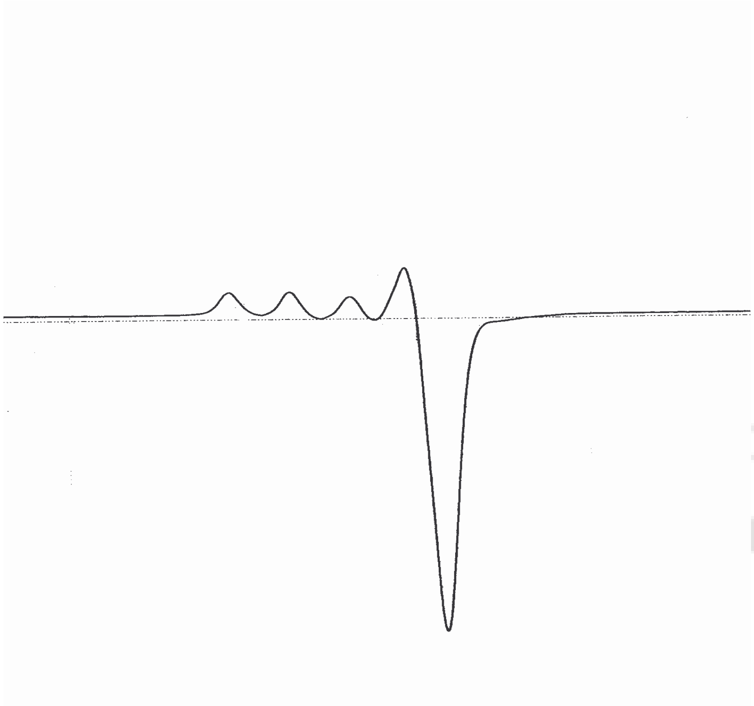


Figure 4. EPR spectra of **4** recorded at liquid N_2 temperatuer in MeOH

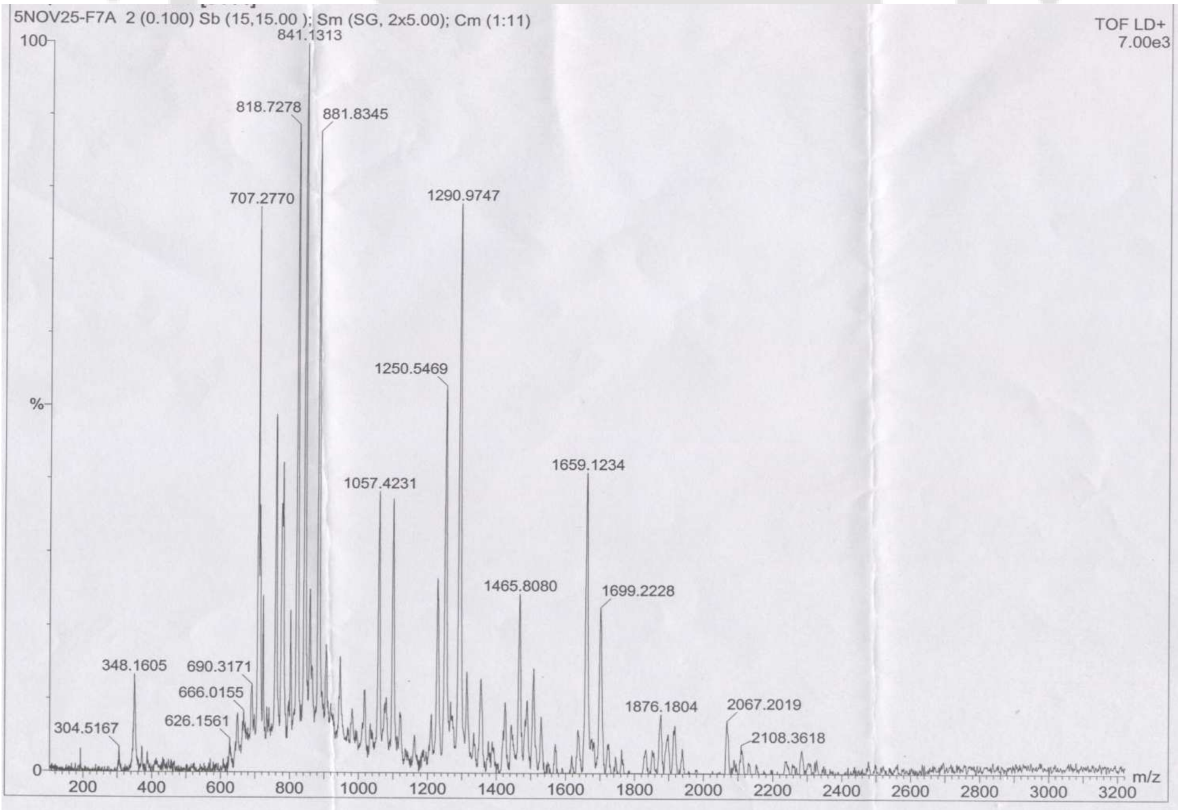
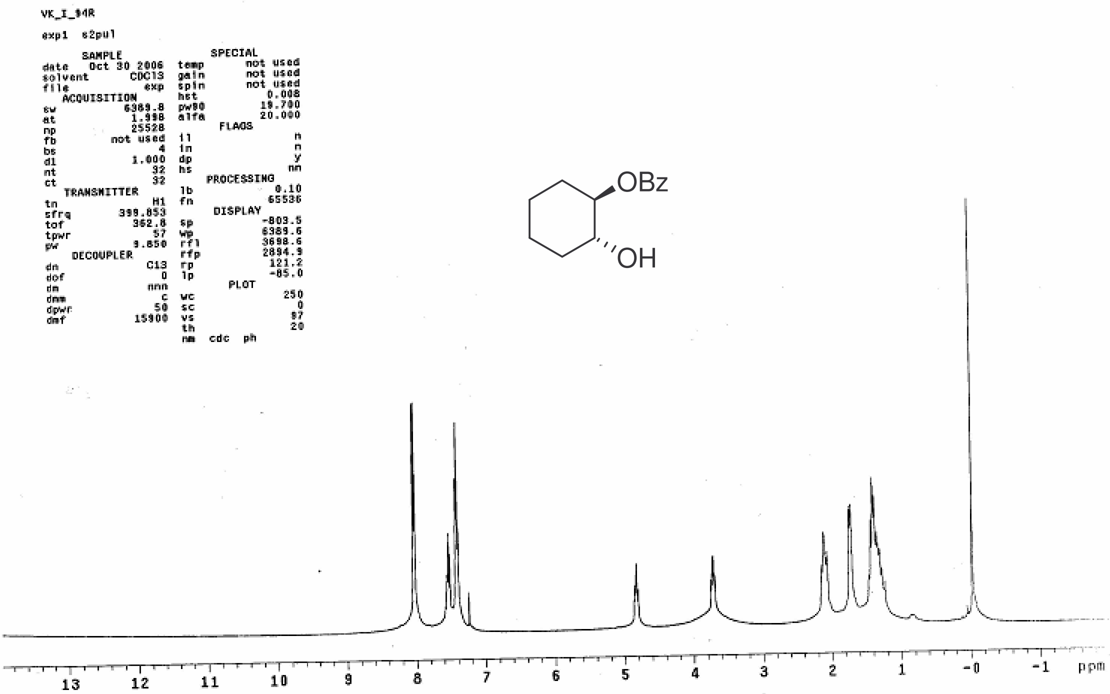


Figure 5. MALDI -TOF mass spectrum of the polymer **4**

Crystal Data and Structure Refinement 4

Identification code	tp02_0m	
Empirical formula	$(C_{21}H_{31}CuNO_3)_n$	
Formula weight	409.06	
Temperature	296(2) K	
Wavelength	0.71073 Å	
Crystal system	Orthorhombic	
Space group	$P2_12_12_1$ Loop xyz 'x, y, z' '-x+1/2, -y, z+1/2' '-x, y+1/2, -z+1/2' 'x+1/2, -y+1/2, -z'	
Unit cell dimensions	a = 6.2168(7) Å	α= 90°.
	b = 16.4734(18) Å	β= 90°.
	c = 21.668(2) Å	γ = 90°.
Volume	2219.0(4) $Å^3$	
Z	2	
Density (calculated)	1.202 Mg/m^3	
Absorption coefficient	1.012 mm^{-1}	
F(000)	814	
Crystal size	0.50x 0.16 x 0.10 mm^3	
Theta range for data collection	6.26 to 28.32 °.	
Index ranges	-8<=h<=8, -21<=k<=-7,-28<=l<=25	
Reflections collected	5416	
Independent reflections	4428 [R (int) = 0.0606]	
Completeness to theta = 28.38°	78.9 %	
Absorption correction	None	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	5416 / 1.016 /245	
Goodness-of-fit on F^2	1.016	
Final R indices [I>2sigma (I)]	$R1$ = 0.0489, $wR2$ = 0.0848	
R indices (all data)	$R1$ = 0.0360, $wR2$ = 0.0785	
Absolute structure parameter	0.014(13)	
Extinction coefficient	0.0000(19)	



```
VK_I_94R

exp1  s2pul

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date   Oct 30 2006   temp           not used
solvent      CDCl3   gain           not used
file           exp   spin           not used
    ACQUISITION      hst               0.008
sw          6389.8   pw90             19.700
at           1.998   alfa             20.000
np           25528          FLAGS
fb        not used   il                    n
bs               4   in                    n
d1           1.000   dp                    y
nt              32   hs                   nn
ct              32        PROCESSING
    TRANSMITTER      lb                 0.10
tn              H1   fn                65536
sfrq       399.853          DISPLAY
tof          362.8   sp               -803.5
tpwr            57   wp               6389.6
pw           9.850   rfl              3698.6
     DECOUPLER       rfp              2894.9
dn             C13   rp                121.2
dof              0   lp                -85.0
dm             nnn            PLOT
dmm              c   wc                  250
dpwr            50   sc                    0
dmf          15900   vs                   97
                     th                   20
                     nm   cdc   ph
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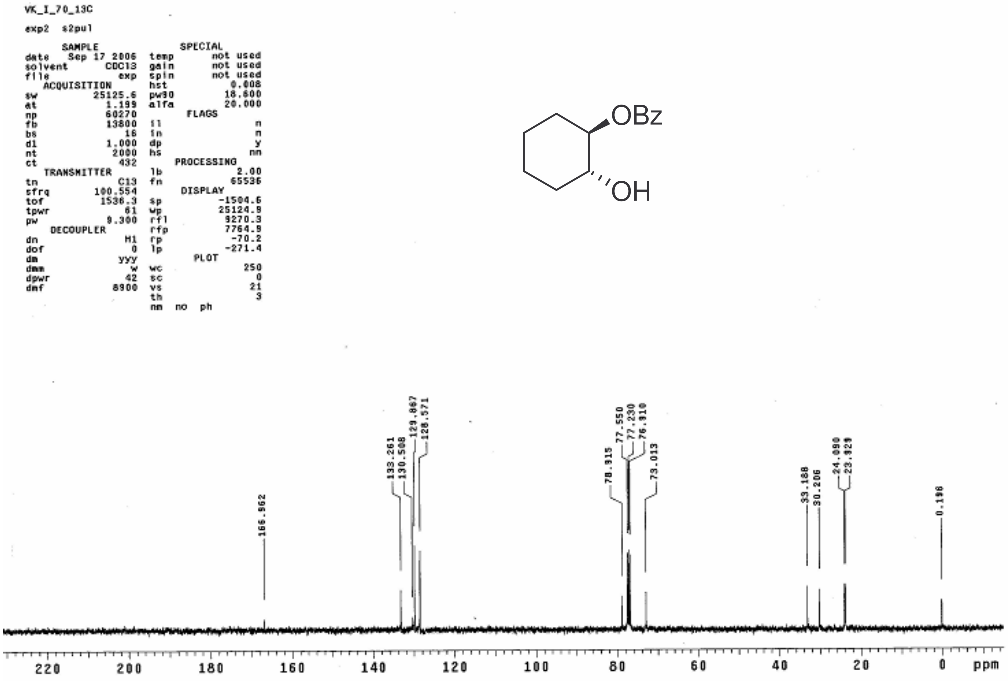

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VK_I_70_13C

exp2  s2pul

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solvent      CDCl3   gain           not used
file           exp   spin           not used
    ACQUISITION      hst               0.008
sw         25125.6   pw90             18.600
at           1.199   alfa             20.000
np           60270          FLAGS
fb           13800   il                    n
bs              16   in                    n
d1           1.000   dp                    y
nt            2000   hs                   nn
ct             432        PROCESSING
    TRANSMITTER      lb                 2.00
tn             C13   fn                65536
sfrq       100.554          DISPLAY
tof         1536.3   sp              -1504.6
tpwr            61   wp              25124.9
pw           9.300   rfl              9270.3
     DECOUPLER       rfp              7764.9
dn              H1   rp                -70.2
dof              0   lp               -271.4
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dmm              w   wc                  250
dpwr            42   sc                    0
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                     th                    3
                     nm   no   ph
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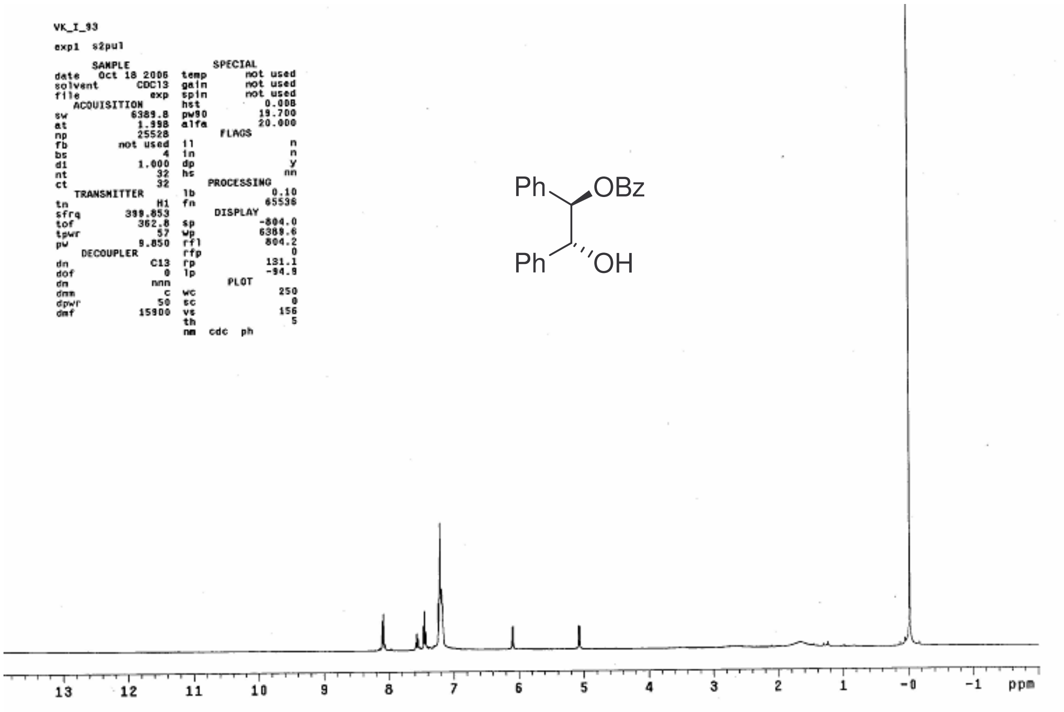

```
VK_I_93

exp1  s2pul

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solvent      CDCl3   gain        not used
file           exp   spin        not used
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sw          6389.8   pw90          19.700
at           1.998   alfa          20.000
np           25528          FLAGS
fb        not used   il                 n
bs               4   in                 n
d1           1.000   dp                 y
nt              32   hs                nn
ct              32        PROCESSING
   TRANSMITTER       lb              0.10
tn              H1   fn             65536
sfrq       399.853          DISPLAY
tof          362.8   sp            -804.0
tpwr            57   wp            6388.6
pw           9.850   rfl            804.2
    DECOUPLER        rfp                0
dn             C13   rp             131.1
dof              0   lp             -94.9
dm             nnn           PLOT
dmm              c   wc               250
dpwr            50   sc                 0
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                     th                 5
                     nm   cdc   ph
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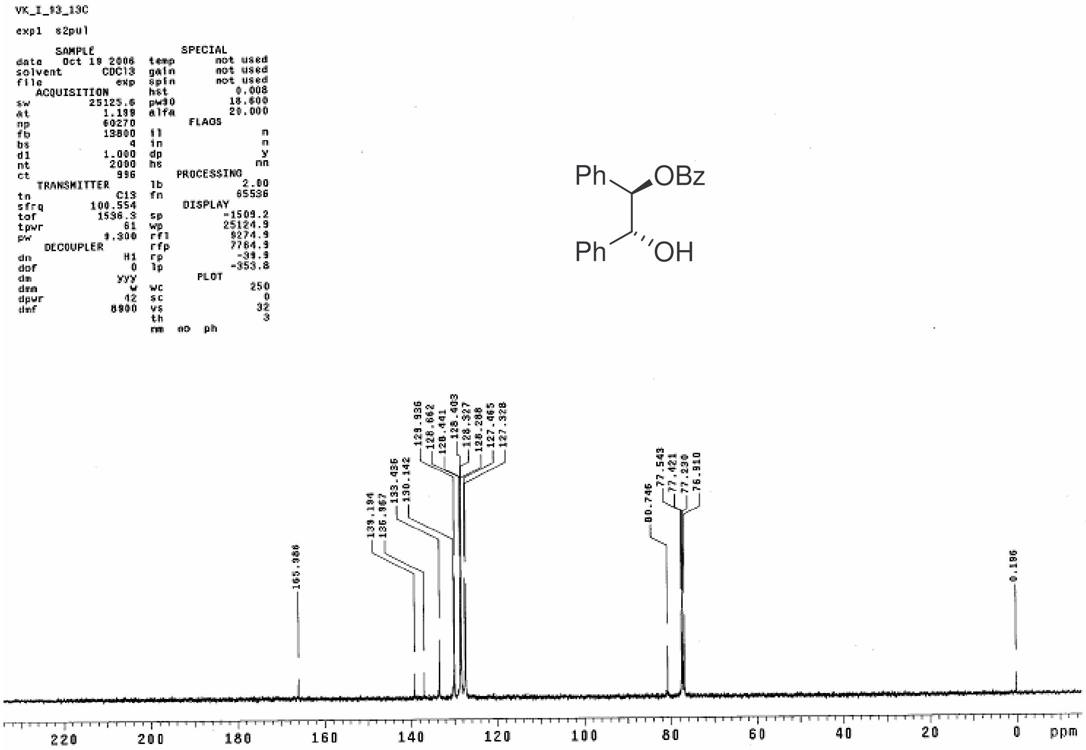

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VK_I_93_13C

exp1  s2pul

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solvent      CDCl3   gain        not used
file           exp   spin        not used
   ACQUISITION       hst            0.008
sw         25125.6   pw90          18.600
at           1.199   alfa          20.000
np           60270          FLAGS
fb           13800   il                 n
bs               4   in                 n
d1           1.000   dp                 y
nt            2000   hs                nn
ct             996        PROCESSING
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tn             C13   fn             65536
sfrq       100.554          DISPLAY
tof         1536.3   sp           -1509.2
tpwr            61   wp           25124.9
pw           9.300   rfl           9274.9
    DECOUPLER        rfp           7764.9
dn              H1   rp             -39.9
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dm             yyy           PLOT
dmm              w   wc               250
dpwr            42   sc                 0
dmf           8900   vs                32
                     th                 3
                     nm   no   ph
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List of Publications

1 Silica-Supported Vanadium-Catalyzed *N*-Oxidation of Tertiary Amines with Aqueous Hydrogen Peroxide.
L. Rout and T. Punniyamurthy, *Adv. Synth. Catal*. **2005**, *347*, 1958.

2 Vanadium-Catalyzed Selective Oxidation of Alcohols to Aldehydes and Ketones with *tert*-Butyl Hydroperoxide.
L. Rout and T. Punniyamurthy, *Adv. Synth. Catal*. **2007**, *349*, 846.

3 Novel CuO Nanoparticle Catalyzed *C-N* Cross-Coupling of Amines with Iodobenzene.
L. Rout, S. Jammi and T. Punniyamurthy, *Org. Lett.* **2007**, *9*, 3397.

4 Efficient CuO Nanoparticle Catalyzed *C-S* Cross Coupling of Thiols with Iodobenzene
L. Rout, T. K. Sen and T. Punniyamurthy, *Angew. Chem. Int. Ed.* **2007**, *46*, 5583.

5 Chiral Linear Polymers Bonded Alternatively with Salen and 1,4-Dialkoxy-2,6-diethynylbenzene: Synthesis and Application to Diethylzinc Addition to Aldehydes.
S. Jammi, L. Rout and T. Punniyamurthy, *Tetrahedron: Asymmetry* **2007**, *17*, 2016.

6 Recent Advances in Copper-Catalyzed Oxidation of Organic Compounds.
T. Punniyamurthy and L. Rout**,** *Coord. Chem. Rev.* **2008**, *252*, 134.

7 Cadmium(II) Catalyzed *C-N* Cross-Coupling of Amines with Aryl Iodides.
L. Rout, S. Jammi and T. Punniyamurthy, *Adv. Synth. Catal.* **2008**, 350, 395.

8 Efficient Copper(I) Catalyzed *C-S* Cross-Coupling of Thiols with Aryl Halides in Water.
L. Rout, P. Saha, S. Jammi and T. Punniyamurthy, *Eur. J. Org. Chem.* **2008**, 640.

9 Efficient Ligand-Free Nickel-Catalyzed *C-S* Cross-Coupling of Thiols with Aryl Iodides.

S. Jammi, P. Barua, L. Rout, P. Saha and T. Punniyamurthy, *Tetrahedron. Lett.* **2008**, *49*, 1484.

10. Synthesis, Crystal Structure and Application of Chiral Copper(II) Polymers for Asymmetric Acylation of Secondary Alcohols.

S. Jammi, L. Rout, P. Saha, V. K. Akhilagunta, S. Sanyasi and T. Punniyamurthy, *Inorg*. *Chem*. **2008**, 47, 5093.

11. CuO Nanoparticle Catalyzed *C-O* Cross Coupling of Hydroxy Compounds and Alcohols with Iodobenzene.

L. Rout, S. Jammi and T. Punniyamurthy (Submitted).

Conferences

12. Stereoregular Chiral Copper(II) Coordination Polymer: Synthesis, Crystal Structure and Application to Kinetic Resolution of Secondary Alcohol.

V. K. Akhilagunta, L. Rout and T. Punniyamurthy, IUPAC Conference; IICT Hydrabad , **2006,** P-40.

13. An Efficient CuO Nanoparticle Natalyzed *C-S* Cross-Coupling of Thiols with Iodobenzene (*Best Award by Council Research Society of India*) Guwahati, India.

L. Rout, T. K. Sen, S. Jammi, P. Barua and T. Punniyamurthy, CRSI Symposium **2007**, P-80.