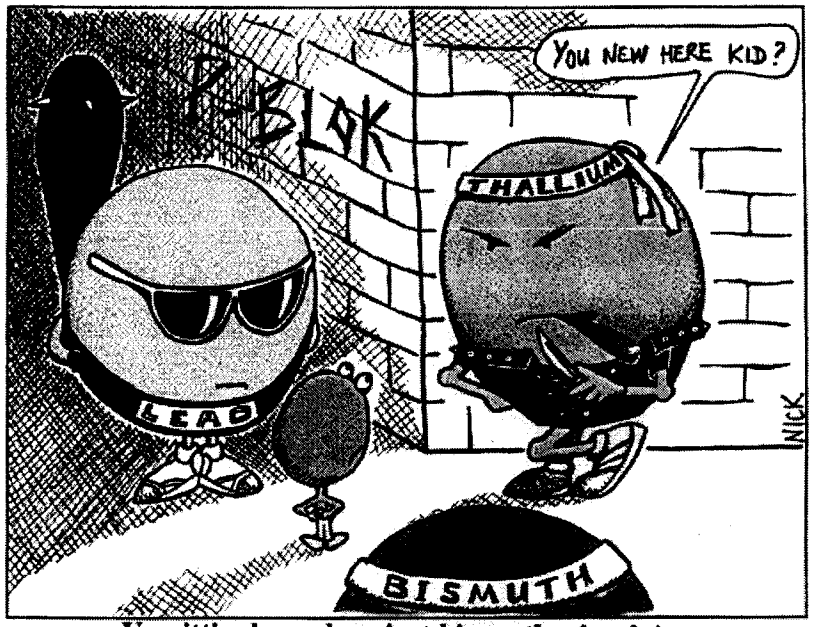
Bismuth Reagents in Organic Transformations



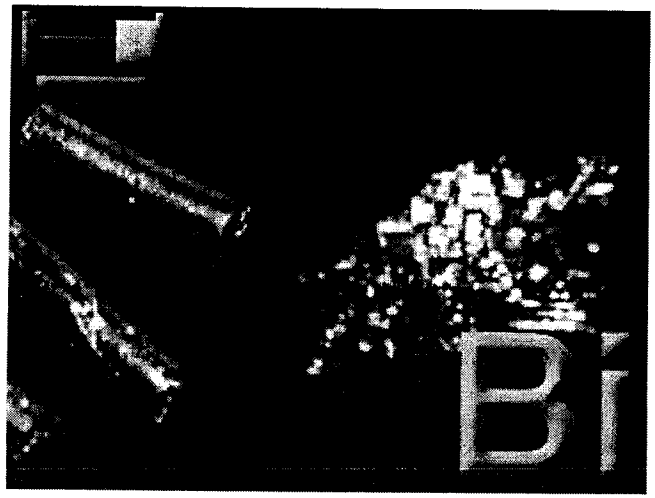
Unwittingly, and against his mother's advice, Vince the first-row transition metal had been lured far away from home, and now found himself surrounded by heavier elements of the P-block.

Shinji Fujimori

Denmark Group Meeting

11/13/01

Element : Bi



Gourp: 15
Atomic Weight: 208.98

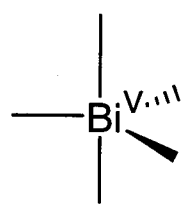
Non-toxic
Inexpensive!
Bi: $2 ~ 3/gram
$Bi(NO_3)_3$-$5H_2O$: $ ~1/gram (ACS grade: $60 for 500g)
$BiCl_3$: $ ~1/gram

Elemental bismuth occurs in Ni, Co, Ag, Sn, and U sulphide ores.
Also found in form of bismuthinite (Bi_2S_3), bismite (α-Bi_2O_3), and bismutite [$(BiO)_2CO_3$]
It is more usual to recover it as a by-product from Pb and Cu smelting plants.

Electronic structure: [Xe]$4f^{14}5d^{10}6s^26p^3$

s-character

Bi(0)



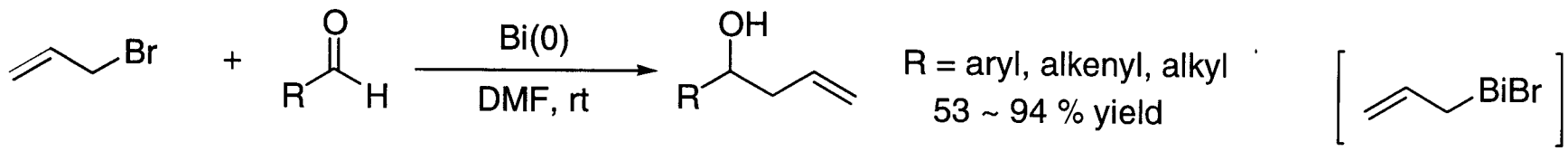
Bi-C Bond:

Ph_3Bi	193.9 ± 10.8 kJ/mol
Ph_3P	321 ± 21 kJ/mol
Ph_3N	373.7 ± 4.2 kJ/mol

www.webelements.com
Finet, J-P. *Chem Rev.* **1989**, *89*, 1487.

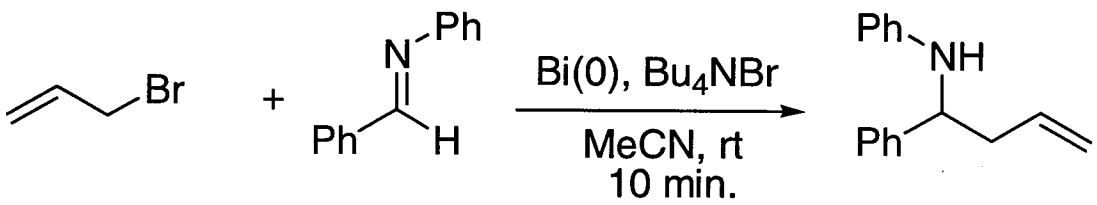
Interaction of Bi(0) to Organic Molecules

Barbier-Type Processes:

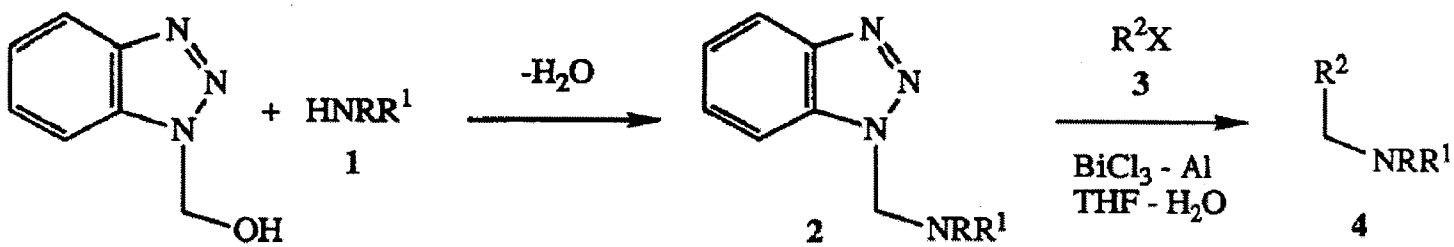


R = aryl, alkenyl, alkyl
53 ~ 94 % yield

- *in situ* formation of Bi(0) was also realized with $BiCl_3$ and Zn or Fe
- Ketones are not reactive



95% yield

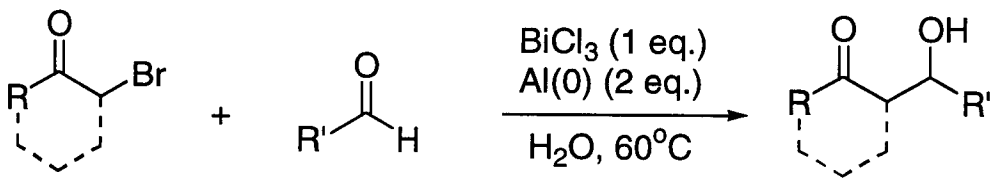


R, R^1 = Me, Ph, etc. R^2 = allyl, propargyl, Me
34 ~ 87% yield

Akiba, K-y. *Tetrahedron Lett.* **1985**, *26*, 4211.
Akiba, K-y. *Tetrahedron Lett.* **1986**, *27*, 4771.
Sandhu, J. S. *Tetrahedron Lett.* **1993**, *34*, 7975.
Katritzky, A. R. *Tetrahedron Lett.* **1991**, *32*, 4247.

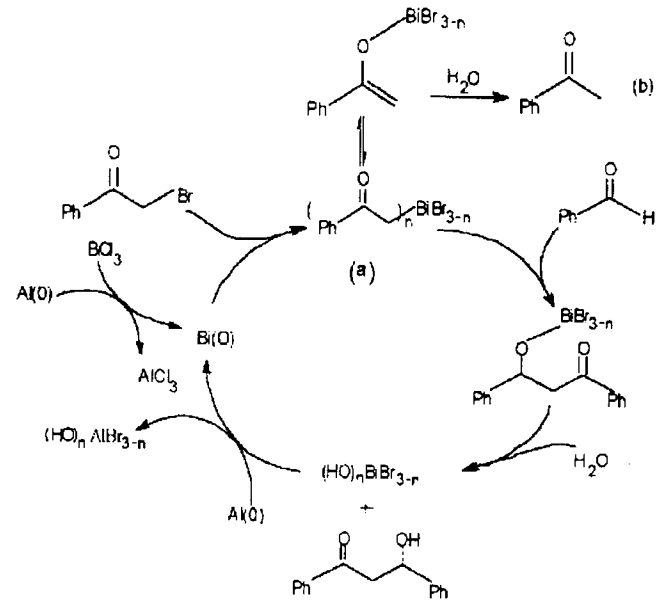
Reactions Involving Bi(0)

Reformatsky Reaction:



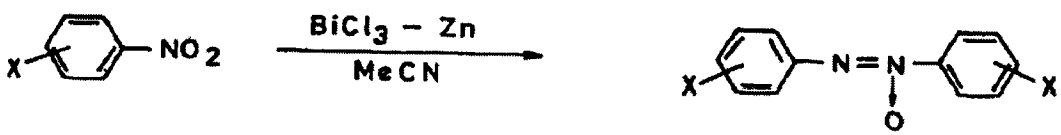
50 ~ 90% yield

Scheme I



Presumed Mechanism of Catalytic $BiCl_3$-Al(0) Mediated Reformatsky Type Reaction

Reductive coupling:



1

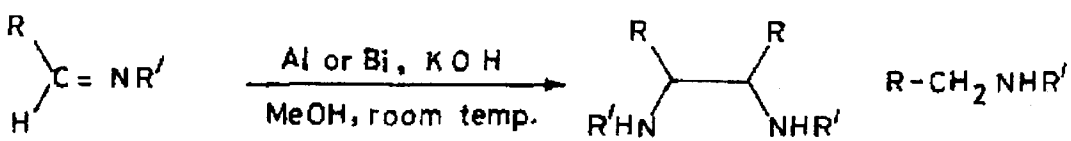
X = *p*-Cl

1hr @ rt

Scheme 1

2

85% yield



1

2

(dl : meso)

3

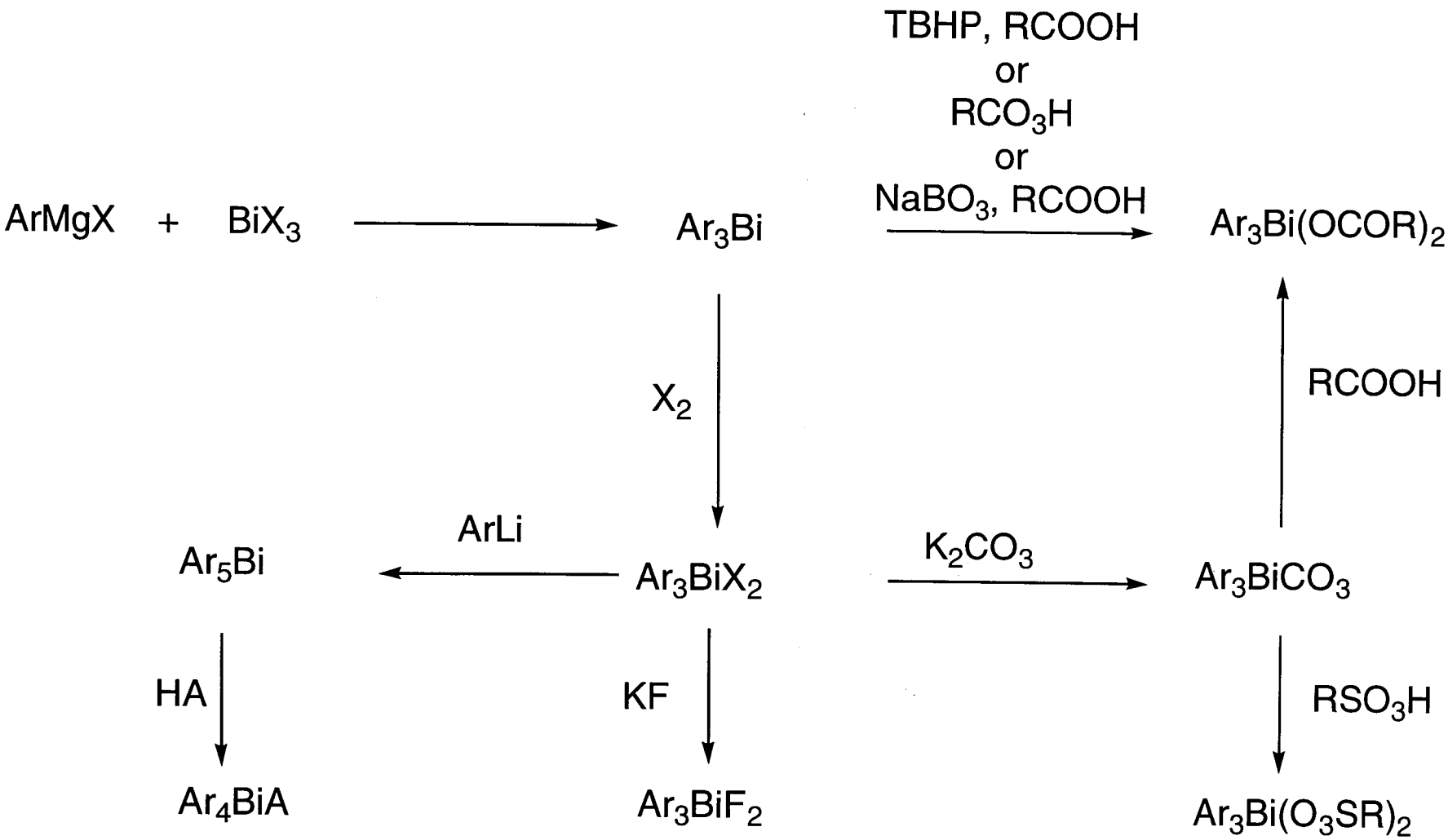
Scheme 1.

R = R' = Ph;
When Al was used: 90% yield (dl/meso = 70/30)
When Bi was used: 75% yield (dl/meso = 60/40)

No **3** was observed.

Zhang, J. *Tetrahedron Lett.* **1997**, *38*, 2733.
Sandhu, J. S. *Tetrahedron Lett.* **1994**, *35*, 3167.
Sandhu, J. S. *Tetrahedron Lett.*, **1995**, *36*, 6747.

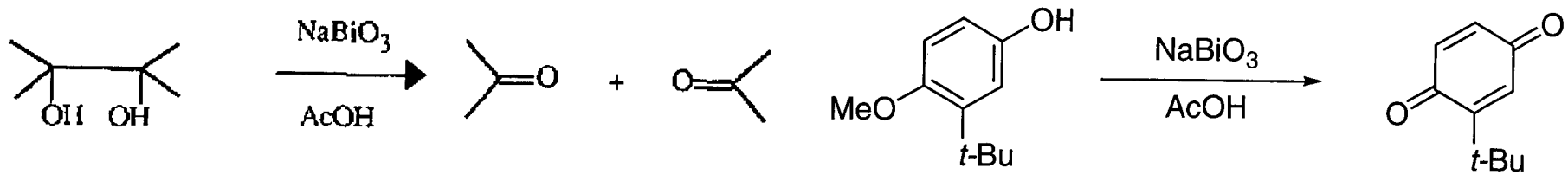
Synthesis of Bi(III) and Bi(V) Species



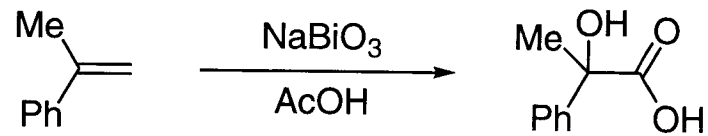
Finet, J-P. *Chem. Rev.* **1989**, *89*, 1487.

Use of Bi(V) Reagents for Oxidation

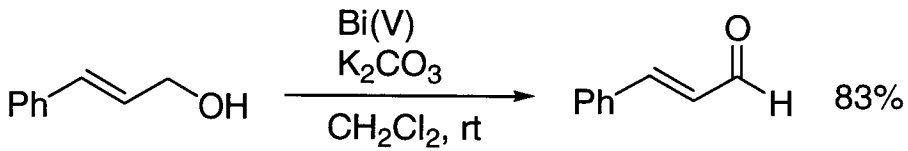
Rigby (1950): $NaBi^{V}O_3$ as oxidazing reagent

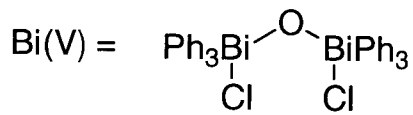


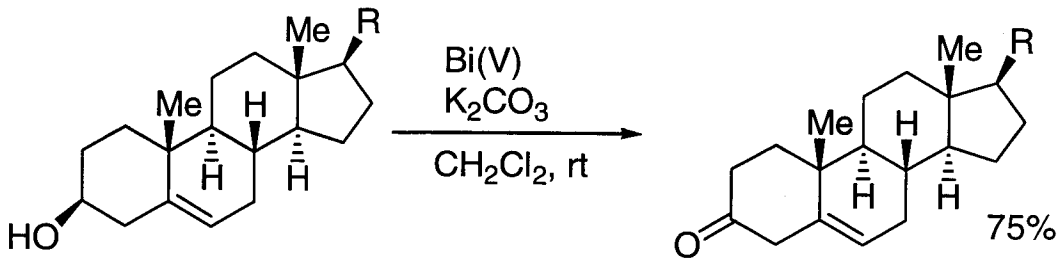
Oxidation occurs in acidic medium.



Barton (1978): Arylbismuth(V) reagents for oxidation



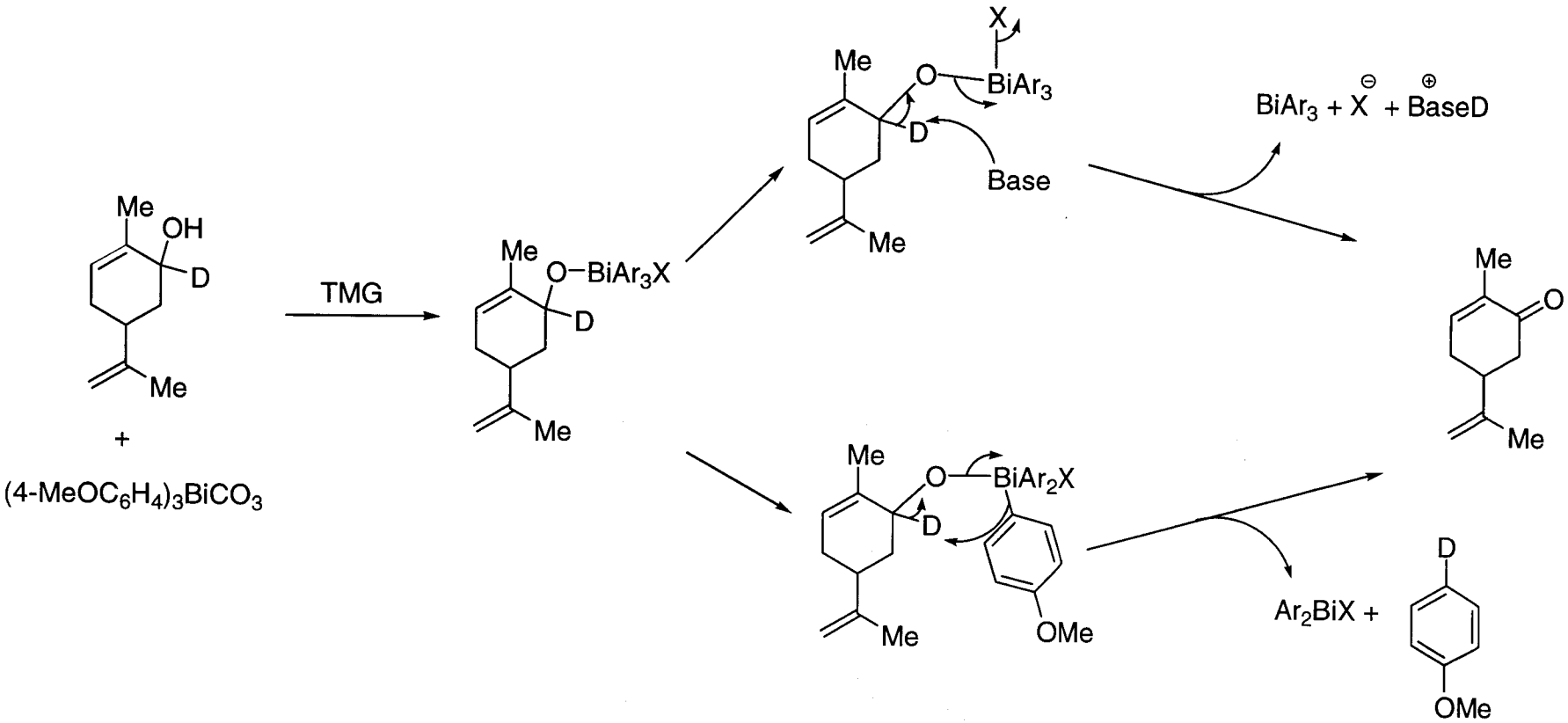




Postel, M.; Dunach, E. *Coord.Chem. Rev.* **1996**, *155,* 127.
Rigby, W. *J. Chem. Soc.* **1950**, 1907.
Barton, D. H. R. *J. Chem. Soc. Chem. Commun.* **1978**, 1099.

Mechanism of Oxidation Using Bi(V) Species

D-labeling experiment:

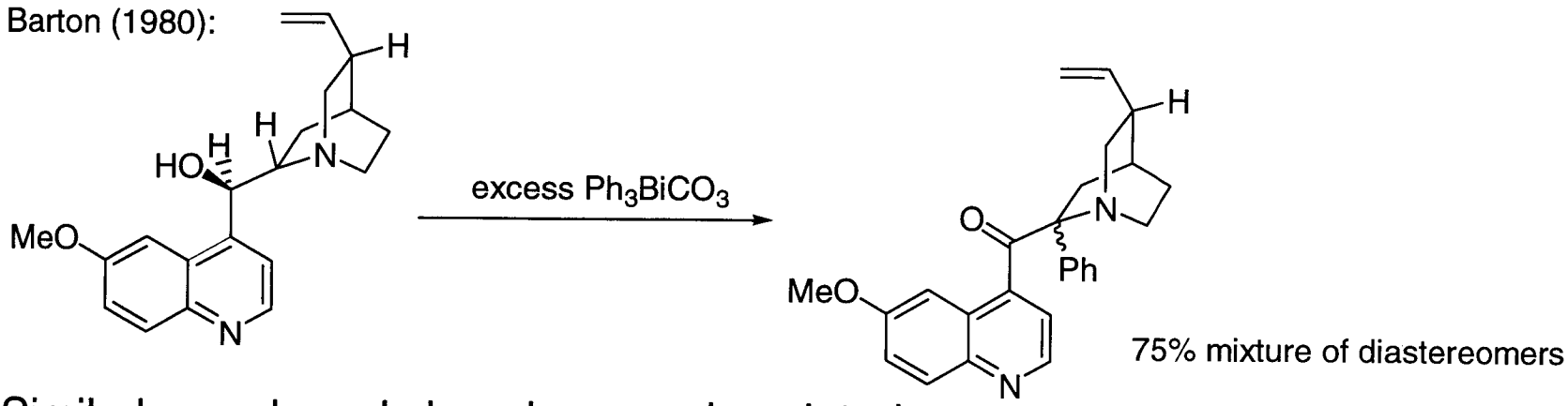


Two pathways are operative.
Similar alkoxybismuth intermediate was observed by NMR.

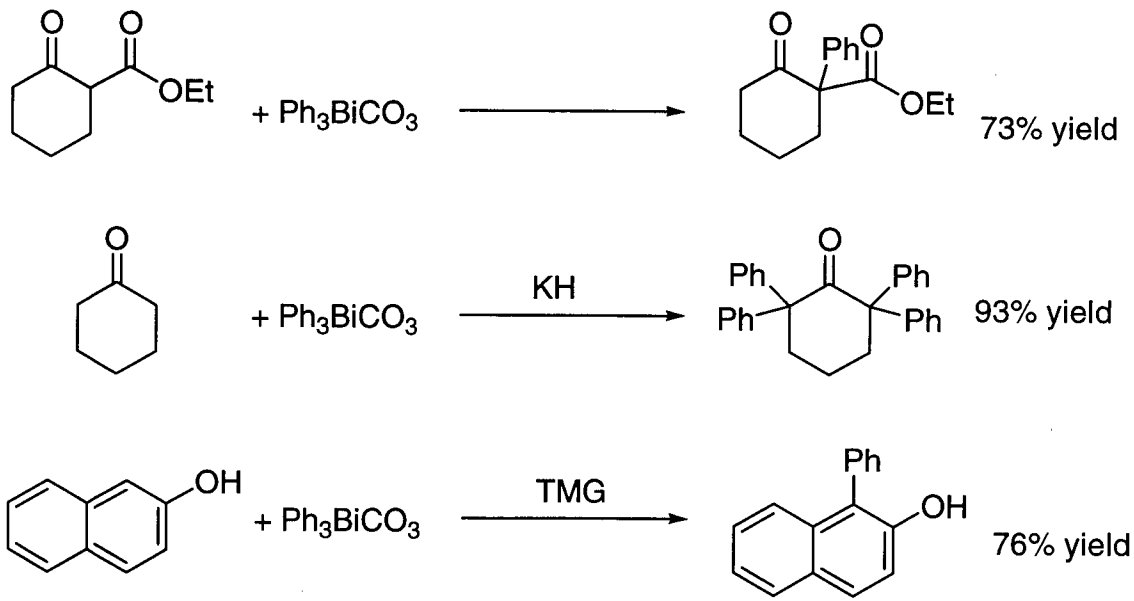
Barton, D. H. R. *J. Chem. Soc. Chem. Commun.* **1980**, 246.
Barton, D. H. R. *J. Chem. Soc. Parkin Trans. 1.* **1985**, 2657.

Phenylation Using Aryl Bi(V) Reagents

Barton (1980):



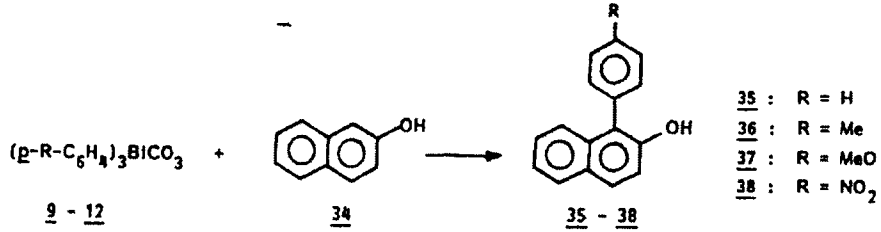
Similarly, enols and phenols were phenylated.

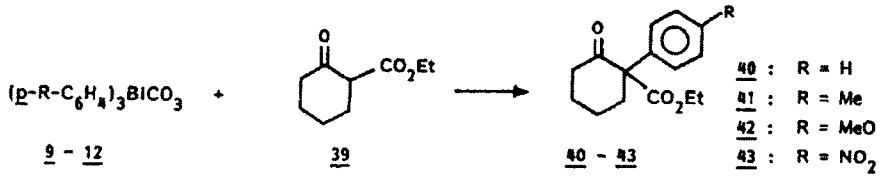


Barton, D. H. R. *J. Chem. Soc. Chem. Commun.* **1980**, 246.
Barton, D. H. R. *J. Chem. Soc. Parkin Trans. 1.* **1985**, 2667.

Mechanism of Ligand Coupling

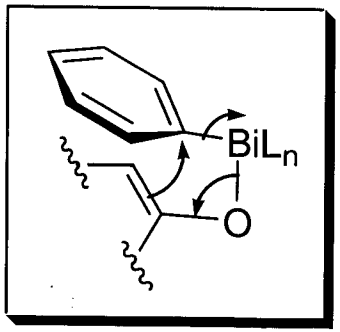
Migratory Aptitude:





-ESR or Radical Trap experiments showed no involvement of free radical species

R	NO_2	H	Me	OMe
Bi ligand coupling	3.55	1	0.45	0.22
Pinacol coupling(cationic)	0.1	1	15.7	500
Radical 1,2-migration	31	1	0.72	0.35



Not cationic, not radical but unsynchronous concerted mechanism was proposed.

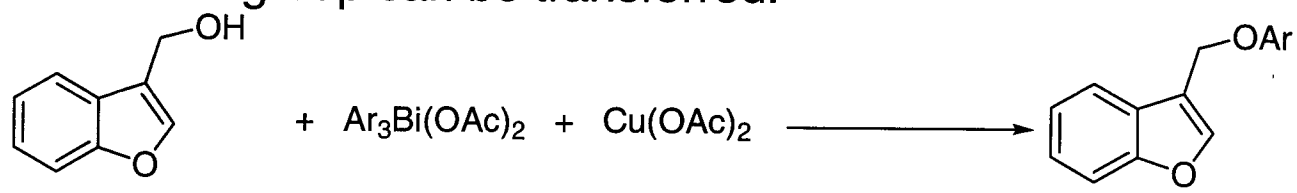
Barton, D. H. R. *Tetrahedron*, **1986**, *42*, 3111.
Finet, J-P. *Tetrahedron*, **1999**, *55*, 3377.

O-Arylation using Aryl Bi(V) and Cu Catalyst

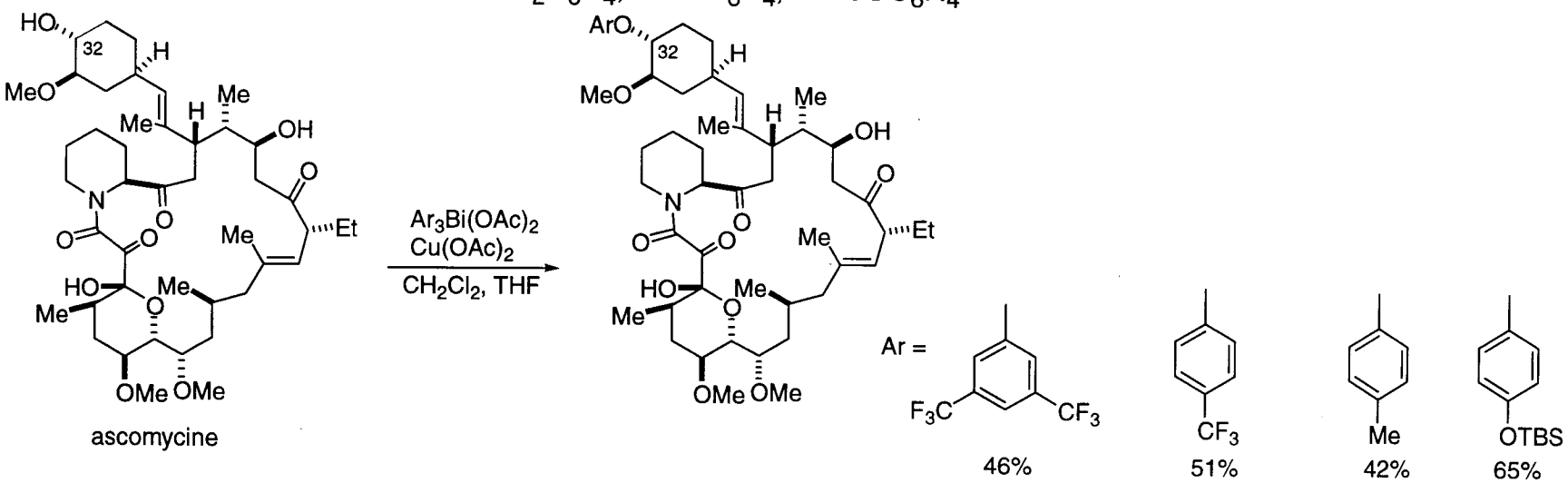
Decomposition of Aryl Bi(V) can be catalyzed by Cu salts (Dodonov):

60 - 95% yield for 1° and 2° alcohols

Various Ar group can be transferred:

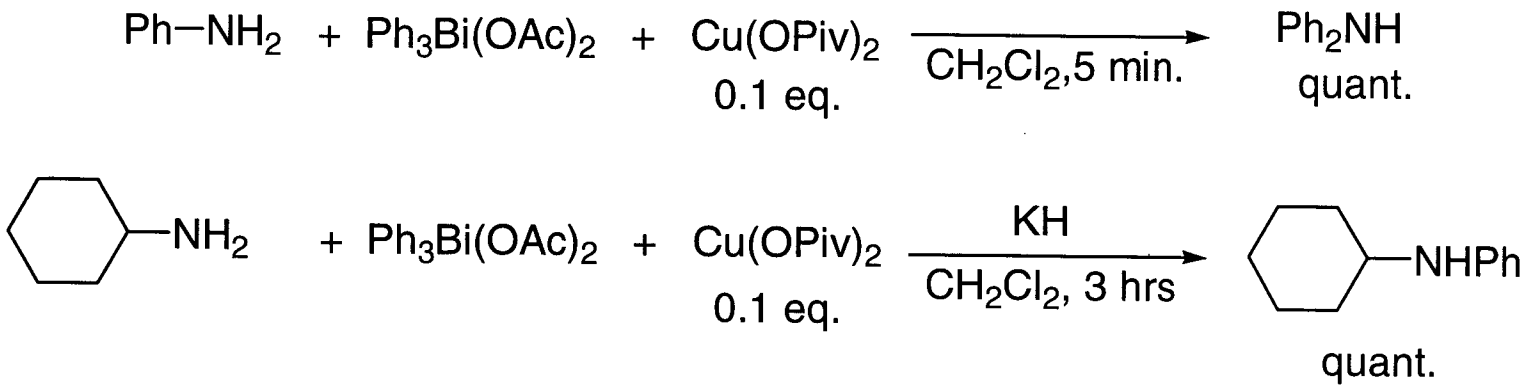


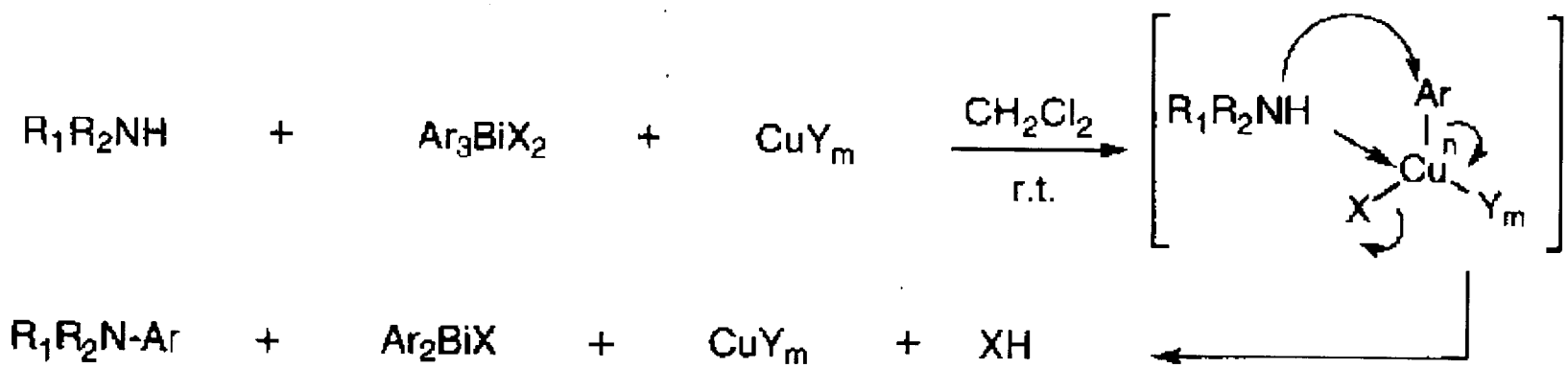
Ar = 3-$NO_2C_6H_4$, 4-MeC_6H_4, 4-$MeOC_6H_4$



Finet, J-P. *Ligand Coupling Reactions with Heteroatomic Compounds*; Pergamon Press: New York, **1998**, pp.192-194.

Phenylation of Amines

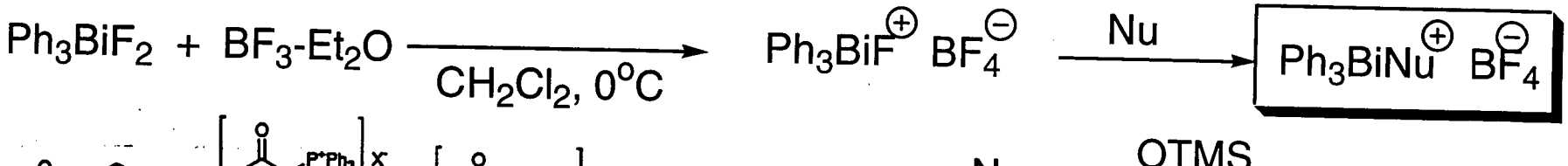


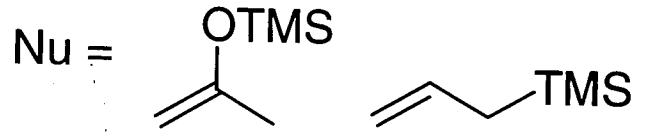


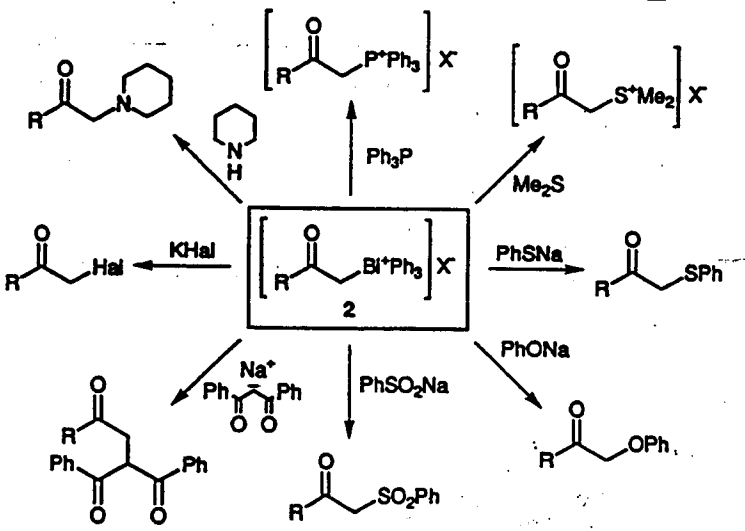
Scheme 2

Barton, D. H. R. *Tetrahedron*. **1997**, *53*, 4137.

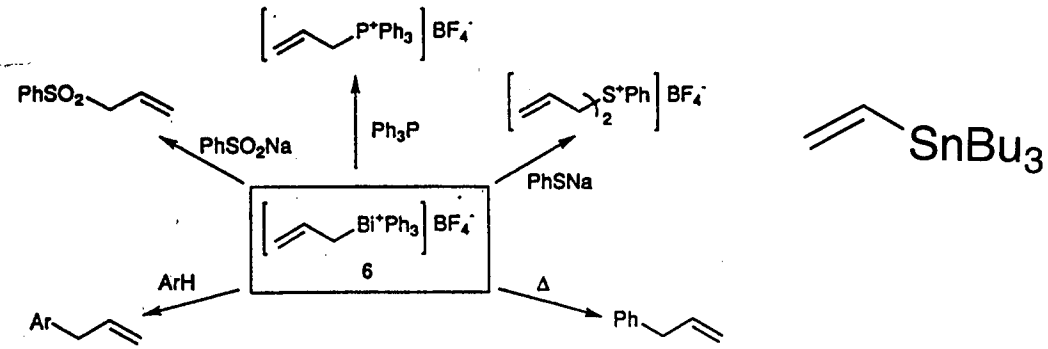
Ligand Coupling with Bismuthonium Salts



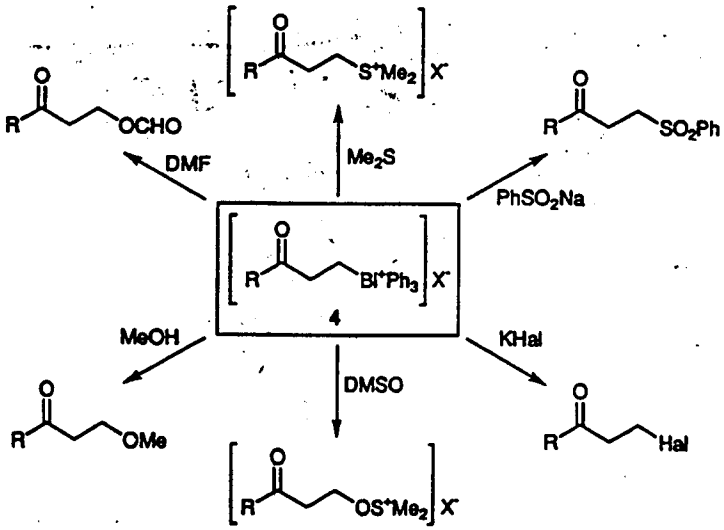




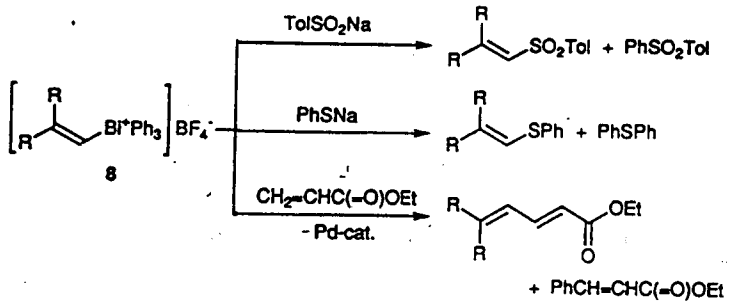
Scheme 4.



Scheme 6.



Scheme 5.

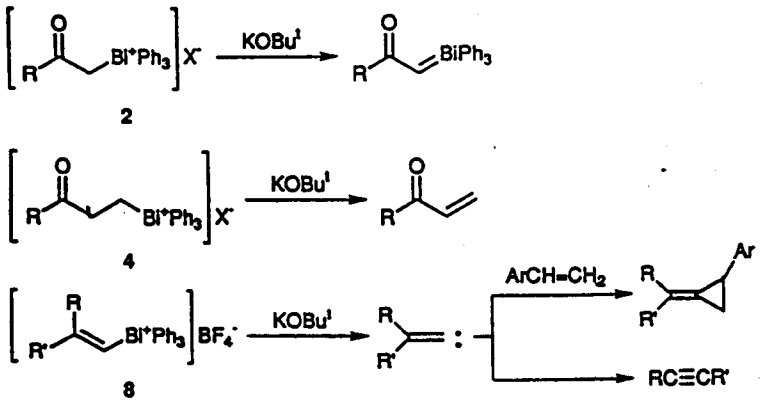


Scheme 7.

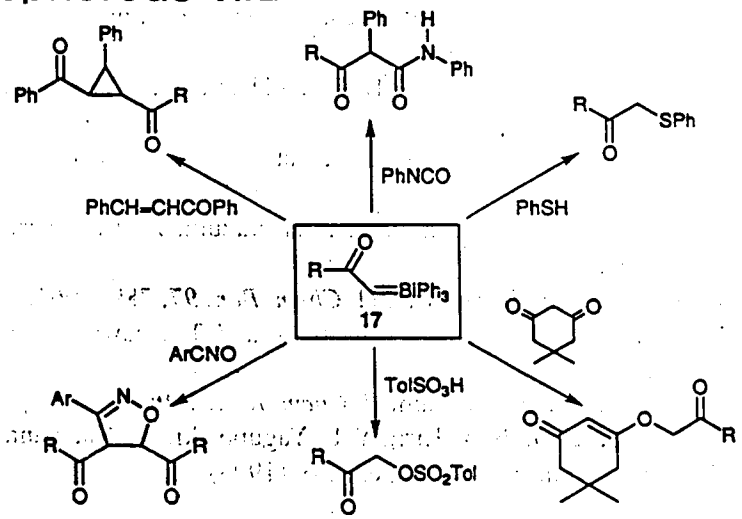
Suzuki, H. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 2673.

Bi-Ylides and Imides

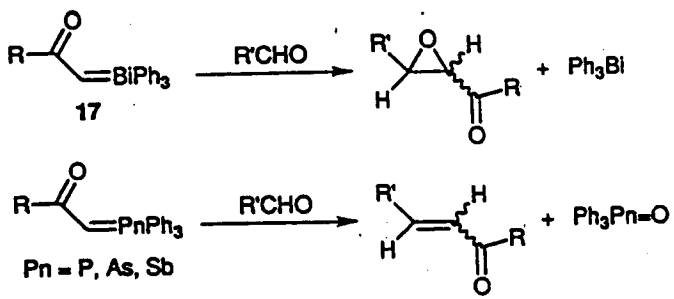
Different reactivity compared to phosphorous vlides.



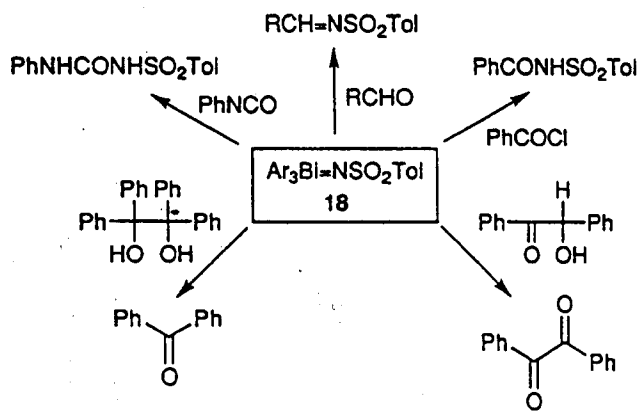
Scheme 8.



Scheme 14.



Scheme 12.

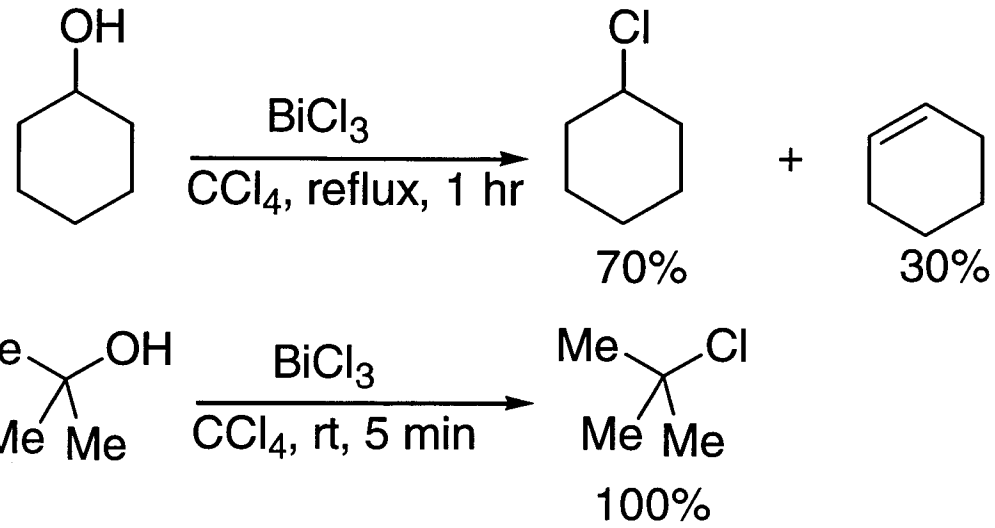


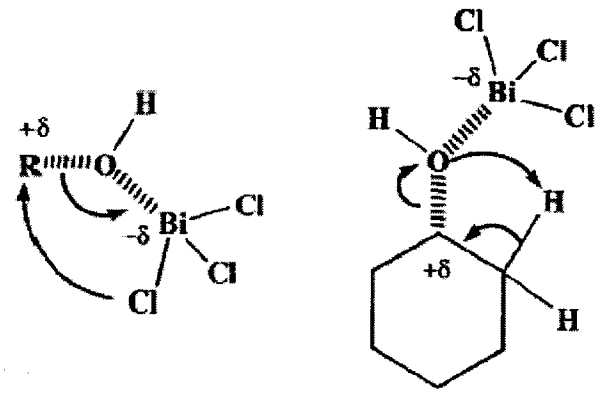
Scheme 16.

Suzuki, H. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 2673.

Halogenation/Etherification using Bi(III)

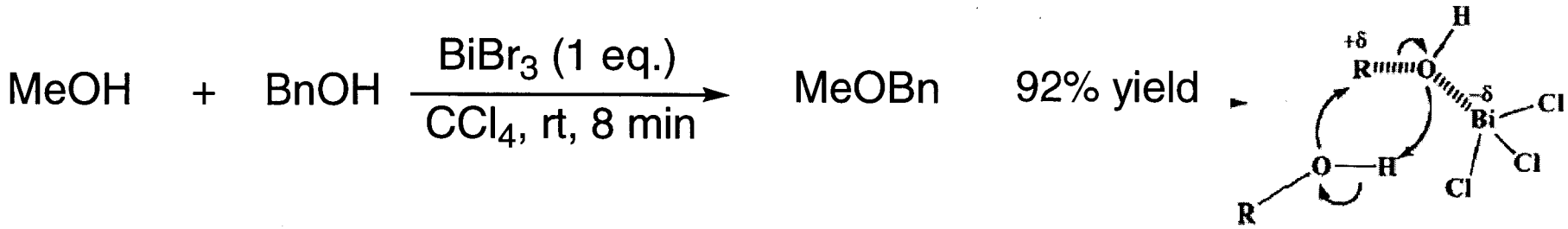
Seondary and tertiary alcohol can be halogenated:





Halogenation Elimination

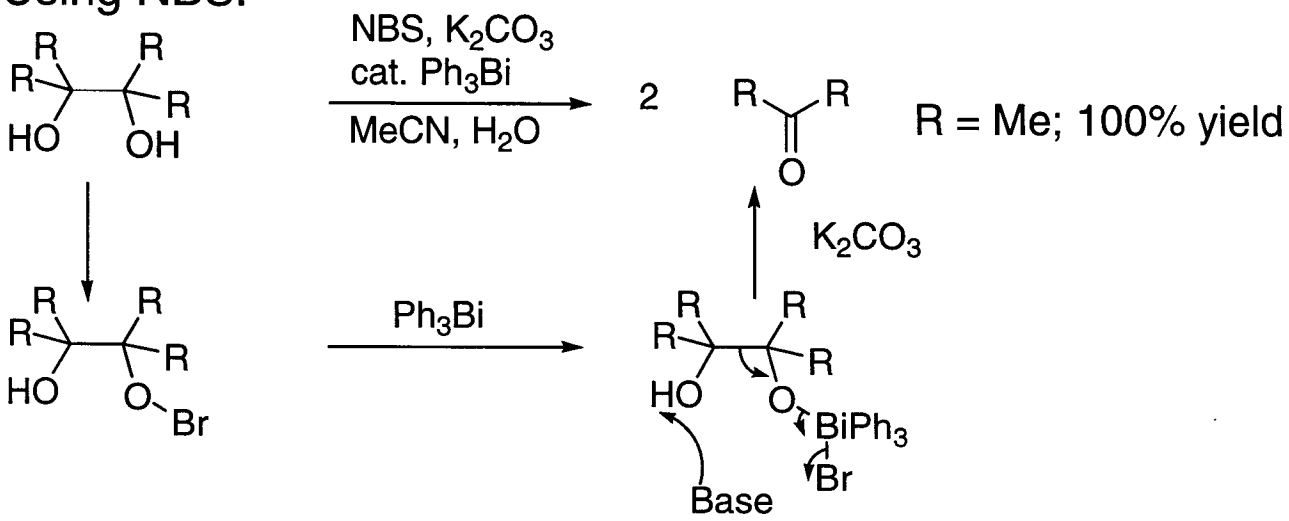
Allylic and benzylic alcohols undergo etherification in presence of BiX_3:

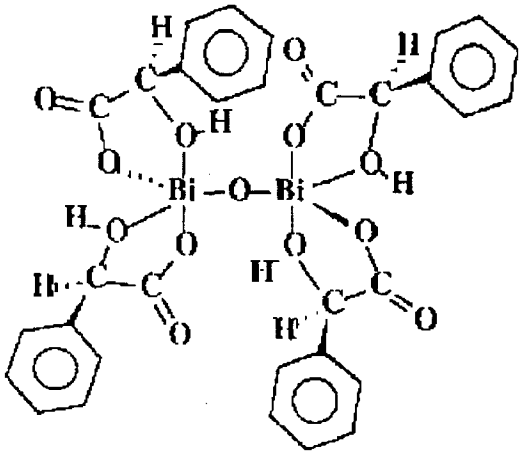


Boyer, B. *Tetrahedron*, **2001**, *57*, 1909.
Boyer, B. *Tetrahedron Lett.* **2000**, *41*, 2891.

Catalytic Use of Bi(III) Reagents: Oxidation

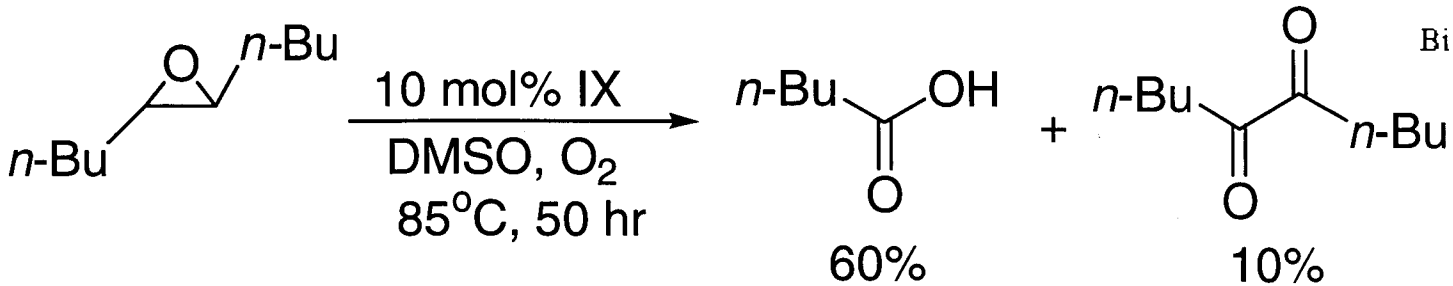
Using NBS:





Bi(mand), (IX)

With molecular oxygen:



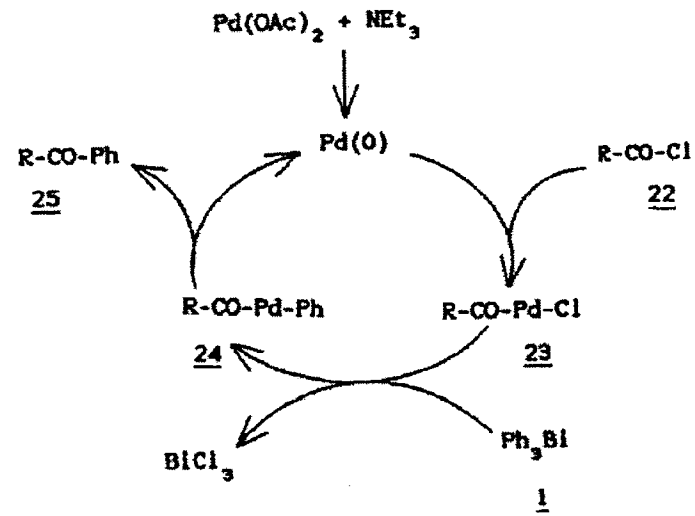
Barton, D. H. R. *J. Chem. Soc. Chem. Commun.* **1982**, 1232.
Postel, M. *Tetrahedron Lett.* **1993**, *34*, 2601.

Ligand Coupling using Triaryl Bi(III)

Pd-catalyzed arylation of acyl chlorides:

$$\underset{\underline{21}}{RCOCl} + \underset{\underline{1}}{Ph_3Bi} \xrightarrow[\text{HMPA, 65°, 5h.}]{Pd(OAc)_2,\ NEt_3} \underset{\underline{25}}{RCO\text{-}Ph} + BiCl_3$$

Entry	RCOCl 22 R=	RCOPh 25 R=	Yield 25 %
1	C_6H_5	C_6H_5	96
2	$C_6H_5\text{-}CH_2$	$C_6H_5\text{-}CH_2$	94
3	CH_3	CH_3	95
4	CH_3CH_2	CH_3CH_2	92
5	$CH_3(CH_2)_{14}$	$CH_3(CH_2)_{14}$ [a]	94
6	Cyclohexyl	Cyclohexyl	91
7	$(CH_3)_3\text{-}C$	$(CH_3)_3\text{-}C$	89
8	1-Adamantyl	1-Adamantyl [b]	90

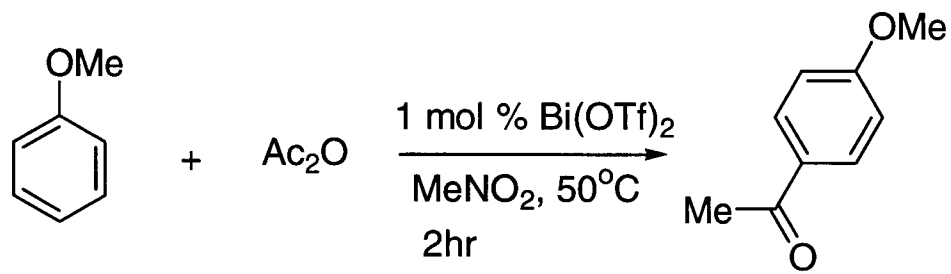


Scheme

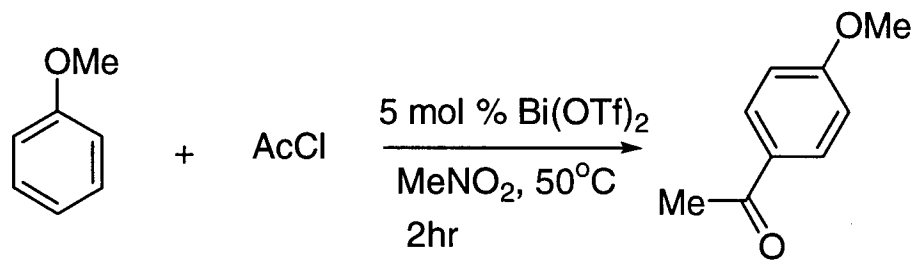
Barton, D. H. R. *Tetrahedron*, **1988**, *44*, 5661.

Bi(III) as a Lewis Acid Catalyst: Friedel-Crafts Acylation

Acylation:

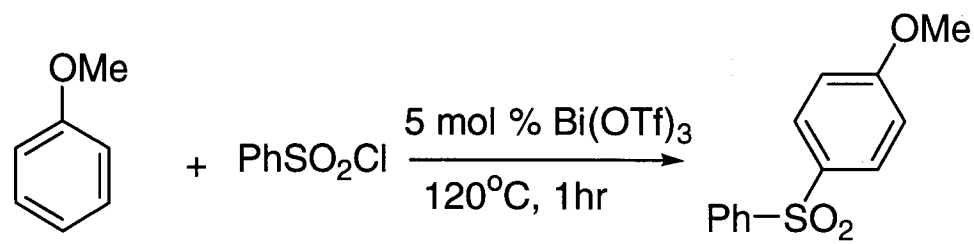


96% yield
o/p = 2/98



80% yield
o/p = 2/98

Sulfonylation:



80% yield
o/p = 48/52

Dubac, J. *Tetrahedron Lett.* **1997**, *38*, 8871.
Dubac, J. *J. Org. Chem.* **1999**, *64*, 6479.

Bi(III) as a Lewis Acid Catalyst: Esterification

Table 1. $Bi(OTf)_3$-catalyzed acetylation of alcohols [Eq. (1)].[a]

$$R{-}OH + Ac_2O \xrightarrow{Bi(OTf)_3} R{-}OAc \qquad (1)$$

Entry	Alcohol	Mol % of the catalyst	Time [h]	Yield [%][b]
1	2-phenylethanol	0.01	0.167	98
2	2-phenylethanol	0.005	2	99
3[c]	2-phenylethanol	0.5	4	92
4	1-phenylethanol	0.005	2	95
5	2-octanol	0.005	17	98
6[d]	2-octanol	0.005	3	98
7	1-adamantanol	0.01	6	98

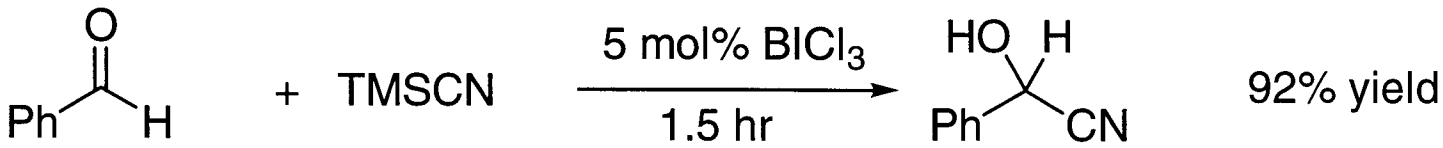
[a] Reaction conditions: alcohol (1.0 mmol), acetic anhydride (10 equiv), 25 °C. [b] Determined by GC. [c] Acetic anhydride (1.5 equiv), CH_2Cl_2 (wet, 1.0 mL). [d] At 40 °C.

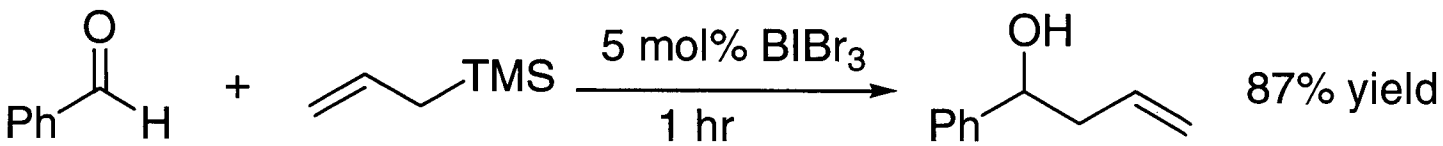
$BiCl_3$, $Bi(TFA)_3$ are also effective catalyst in acylation

Otera, J. *Angew. Chem. Int. Ed.* **2000**, *39*, 2877.
Mohammadpoor-Baltork, I. *Tetrahedron*, **2001**, *57*, 5851.

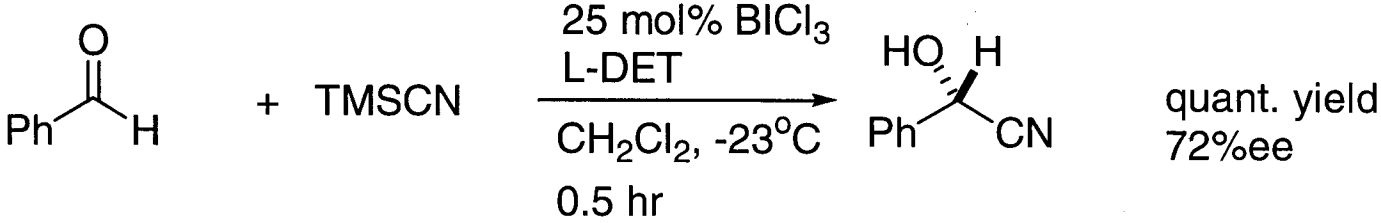
Bi(III) as a Lewis Acid Catalyst: Addition to Carbonyl Group

CN and allyl addition:

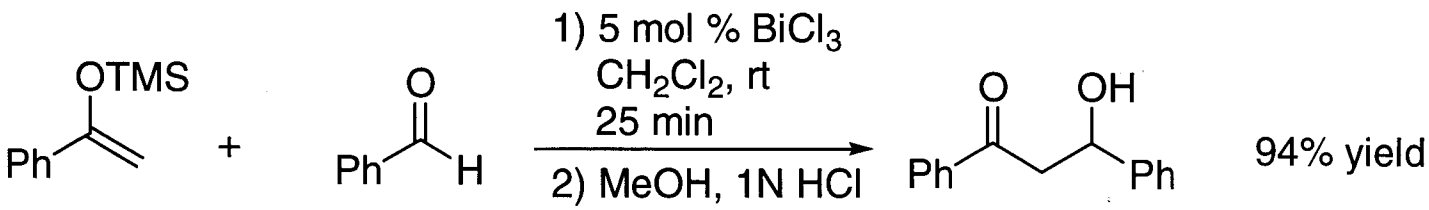




Asymmetric variant:



Mukaiyama-type aldol addition:



Suzuki, H. *Tetrahedron Lett.* **1997**, *38*, 7215.
Wada, M. *Tetrahedron Asymm.* **1997**, *8*, 3939.
Akiba, K-y. *Tetrahedron Lett.* **1988**, *29*, 4619.

Bi(III) as a Lewis Acid Catalyst: Diels-Alder Reaction

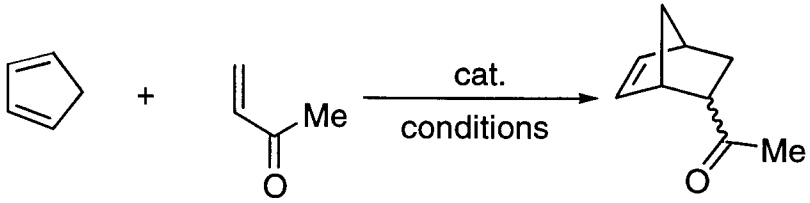
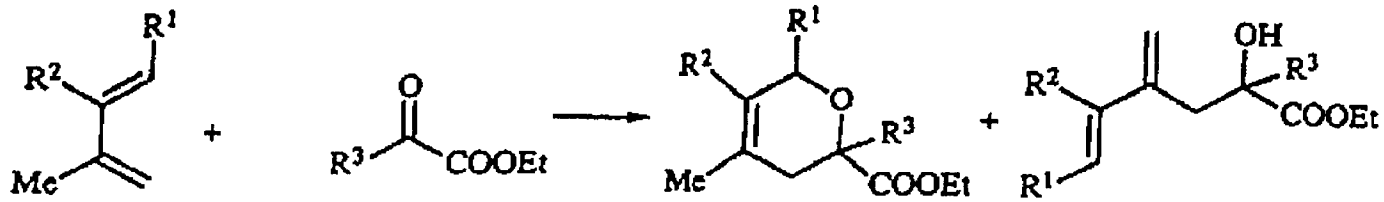
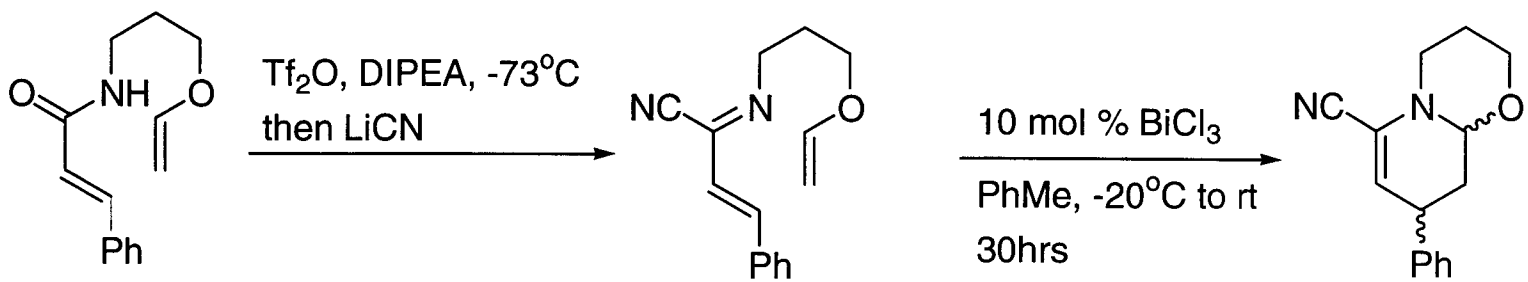


Table 1. Diels–Alder Reactions Catalyzed by Various Lewis Acids

entry	reaction	catalyst (mol %)	experimental conditions[a]	product and isomers	% yield[b]
1	**1** + **4**	$Sc(OTf)_3$ (10)	0 °C; 12 h	**8** (89/11)[d]	96[c]
2	**1** + **4**	$Bi(OTf)_3$ (1)	0 °C; 4 h	**8** (93/7)[d]	87
3	**1** + **4**	$BiCl_3$ (10)	0 °C; 2 h	**8** (95/5)[d]	86



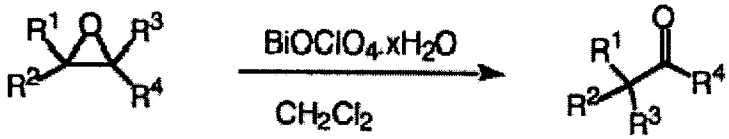
$R^1 = R^2 = H$; $R^3 = H$ @ 60°C 30 min. 96% yield, ratio 90/10



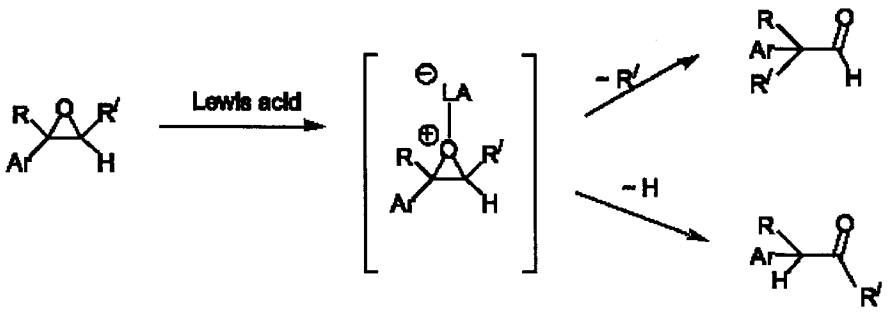
82% yield
cis/trans = 1/8.3

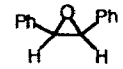
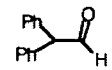
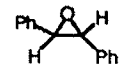
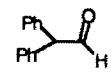
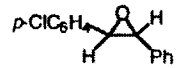
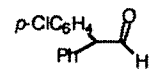
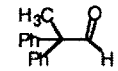
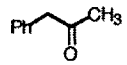
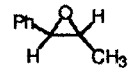
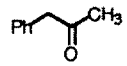
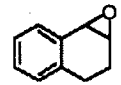
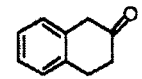
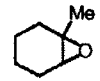
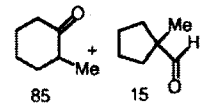
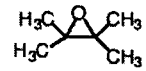
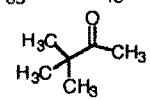
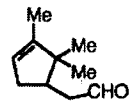
Dubac, J. *J. Org. Chem.* **1997**, *62*, 4880.
Dubac, J. *Tetrahedron Lett.* **1998**, *39*, 1161.
Motorina, I. A. *Tetrahedron Lett.* **1999**, *40*, 7215.

Bi(III) as a Lewis Acid Catalyst: Epoxide Rearrangement



$Bi(OTf)_3$-x H_2O also works.

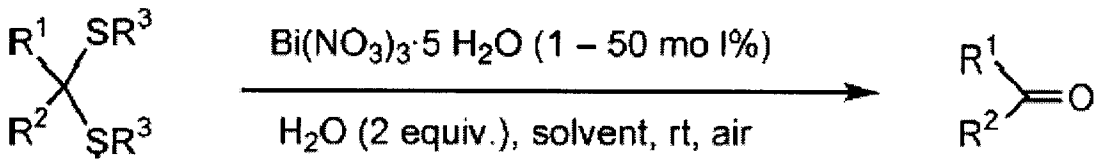


Entry[a]	Epoxide	Time[b]	Product	Yield (%)[c]
1[11]		25 min		90
2		45 min		90
3[12]		45 min		90
4[2d]		45 min		68
5		45 min		70
6		45 min		70
7		45 min		70
8[2b]		1 h	 85 15	71[d]
9[9]		1h		75[e]
10[10]		40 min		88

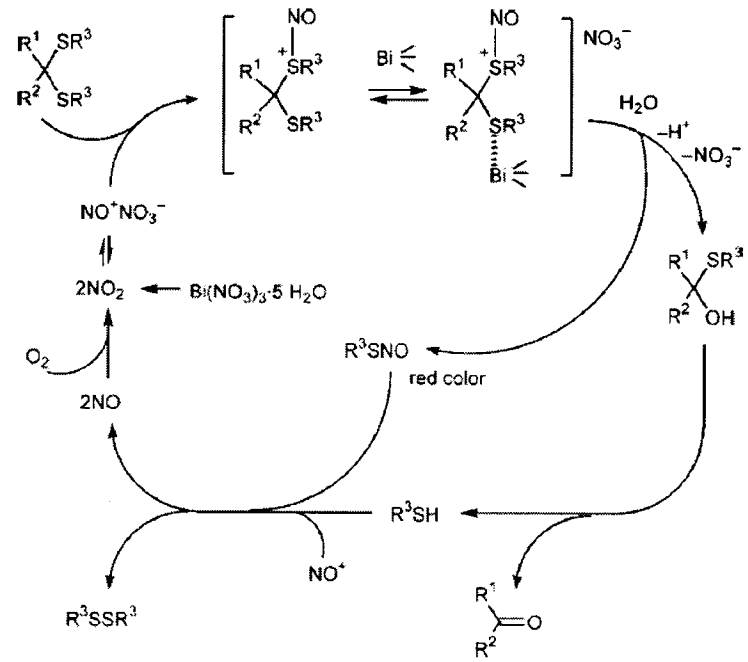
[a]Superscripts against entry # refer to literature reference for product. [b]All reactions were run at room temperature. [c]Yields refer to isolated, purified product. [d]The ketone:aldehyde ratio in the crude product mixture was determined by GC analysis to be 85:15, respectively. [e]Due to volatile nature of the product, the solvent was removed at atmospheric pressure using a water bath at 50 °C.

Mohan, R. S. *Tetrahedron Lett.* **2000**, *41*, 1527.
Mohan, R. S. *Tetraheron Lett.* **2001**, *42*, 8129.

Bi(III) as a Lewis Acid Catalyst: Deprotections



Scheme 1.



Scheme 2.

Komatsu, N. *Adv. Synth. Catal.* **2001**, *343*, 473.
Mohan, J. S. *J. Org. Chem.* **2000**, *65*, 8399.
Sabitha, G. *Adv. Synth. Catal.* **2001**, *343*, 169.
Bajwa, J. S. *Tetrahedron Lett.* **2000**, *41*, 6021.

Conclusion

- Bi reagents have been used in various organic transformations for a long time.
- Different oxidation states showed very different reactivity.
- Bi(V) reagents and their reactions are well studied. (Barton, Finet, Suzuki)
- Recent studies on Bi(III) reagents are more focused on Lewis acid catalysis.
- Weak C-Bi bond strength: useful arylation reactions