PERKIN 1

Heteroaromatic ethers of phenols in nickel-catalysed *ipso*-replacement reactions with magnesium, zinc and tin organometallic compounds

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Received (in Cambridge, UK) 17th February 2000, Accepted 28th March 2000
Published on the Web 9th May 2000

Phenols are readily converted in high yield into the heterocyclic ethers, 5-aryloxy-1-phenyl-1*H*-tetrazole, **1** and 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxide, **2**. X-Ray crystallographic analysis and other evidence shows that, in these ethers, the originally strong phenolic C–OH bond is considerably weakened on derivatization. In nickel-catalysed cross-coupling reactions with organozinc and organotin compounds, the heterocyclic parts of ethers **1**,**2** provide good nucleofuges. In similar cross-coupling reactions with organomagnesium halides, ethers **1** again provide good nucleofuges but, in marked contrast, ethers **2** do not. In all reactions, palladium based catalysts were mostly not effective.

Introduction

ipso-Substitution of phenolic OH groups to give other functionalities is of considerable relevance to synthesis because of their natural abundance and availability as petrochemicals.[1] To effect such substitution, activation of the OH group is necessary. This requirement for activation has led to the derivatization of phenols to give ethers or esters, in which the original C–OH phenolic bond has been changed from its partial double bond nature (bond order about 1.5) to become more like the single bond found in aliphatic ethers or alcohols (bond order, 1). The most efficient derivatives seem to be those in which the phenolic hydroxy is connected to a very strongly electron-withdrawing group, as with the triflates.[2,3] These derivatives become similar to aryl halides in that catalysed *ipso*-substitution reactions can be carried out under the same sort of mild conditions as those used with aryl bromides or iodides. These "halogenoid" derivatives have been mostly triflates up to now. For example, aryl triflates undergo palladium-catalysed cross-coupling with a wide variety of organotin compounds. This "Stille coupling" method has proved to be a more efficient and general method than previous similar nickel-catalysed cross-couplings of aryl triflates with Grignard reagents, and has been widely used for transformations of a variety of halo- or boron-substituted compounds.[4] Also, it has been shown that aryl triflates do undergo easy cross-coupling when catalysed by nickel in combination with lithium bromide.[5] One limitation seems to be the low yields and lack of selectivity observed in the coupling of allyltin compounds with aryl triflates and there is still a need for more practical alternative ethers or esters of phenols, capable of providing selectivity in the presence of other functional groups that may be present.[6]

5-Chloro-1-phenyl-1*H*-tetrazole or the more cost-effective 3-chloro-1,2-benzothiazole 1,1-dioxide (pseudosaccharyl chloride) react easily with phenols to give highly crystalline, stable *O*-ethers **1**,**2**, which provide good nucleofuges in catalysed reactions.[7] For both ethers, the side-product nucleofuges (saccharin or 5-phenyltetrazolone) are water soluble and easily separated from the required reaction products by extraction. Under suitable reductive conditions, ethers **1**,**2** undergo efficient hydrogenolysis (formally, an *ipso* replacement by hydrogen) either with hydrogen gas under pressure[8] or, more conveniently and selectively, through heterogeneous catalytic transfer hydrogenolysis, using a suitable hydrogen donor.[9,10] Recently, catalytic transfer reduction of 1-phenyl-1*H*-tetrazol-5-yl ethers of allylic alcohols has been effected without concomitant reduction of the double bond in the allyl group.[11] It has been shown also that ethers **1** undergo easy nickel-catalysed reaction with organomagnesium halides to give cross-coupled products.[12] For these large molecules, based on tetrazoles there are no known hazards although toxicity of some tetrazoles has been reported.[13]

In the present work, this sensitivity of the ethers **1**,**2** to cross-coupling reactions has been extended to organozinc and organotin compounds, using nickel or palladium catalysts. None of the reported yields is optimised.

Results and discussion

X-Ray crystallographic structural analysis of phenols and their ethers **1**,**2** reveals that the C–O bond in phenols and their simple ethers has a length of about 134 pm but, in the heteroaromatic ethers, it is much longer at about 143 pm (bond *a* in **1** or **2**). At this last length, the C–O bond is as long as or even longer than those in aliphatic alcohols or ethers.[14] The result of this large increase in bond length is that the original phenolic C–OH bond has been considerably weakened after conversion of the phenol into its heterocyclic ether **1**,**2**. At the same time that the original phenolic C–O bond lengthens, the other ether C–O bond between oxygen and the heterocycle (bond *b* in **1** or **2**) becomes as short (133 pm) as in the original phenolic C–O bond.[7] In effect, the heterocycles shift electron density from the original phenolic C–OH bond into the new ether bonds (*b*) in the ethers **1**,**2**; the phenol becomes a "halogenoid". Semi-empirical calculations at the MOPAC PM3 level show that the carbon of the phenolic C–OH bond has a partial electronic charge density of +0.10 but that this changes to +0.33 on conversion of the phenol into the phenyl ether **1** (Ar = Ph).[15]

On the basis of these structural changes and the apparent similarities in the mechanisms of catalytic transfer reduction[16] and cross-coupling,[17] it was anticipated that the ethers **1**,**2** should undergo easy catalytic cleavage by oxidative addition to a metal, an essential first step to cross-coupling. It has been

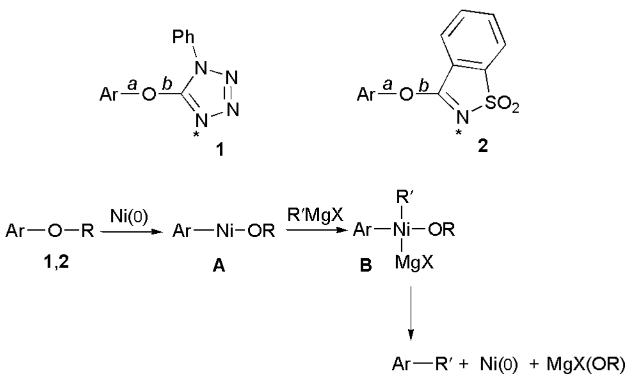
DOI: 10.1039/b001333l

Table 1 Cross-coupling of 5-aryloxy-1-phenyl-1*H*-tetrazoles **1** or 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxides **2** (Ar–O–R) and diethylzinc with transition metal catalysts

Ar–O–R					
Ar	R[a]	Catalyst preparation[b]	Solvent	Time/h	Yield (%)[c]
Phenyl	S	NiCl$_2$(dppp)/DIBAL-H	THF	4	74
Phenyl	S	NiCl$_2$(dppp)	THF	10	0
4-Acetylphenyl	S	NiCl$_2$(dppp)[d]	Dioxane	12	42[e]
4-Acetylphenyl	T	Ni(acac)$_2$/PPh$_3$/DIBAL-H	Dioxane	6	35[e]
2-Naphthyl	T	NiCl$_2$(dppp)/DIBAL-H	THF	1.2	73
Phenyl	T	NiCl$_2$(dppp)/DIBAL-H	THF	2	70
2-Naphthyl	S	Ni(acac)$_2$/PPh$_3$/DIBAL-H	Dioxane	3	59[f]
2-Naphthyl	T	Ni(acac)$_2$/PPh$_3$/DIBAL-H	Dioxane	4	52[g]
2-Naphthyl	S	Ni(acac)$_2$/PPh$_3$/DIBAL-H	Dioxane	3	39[g]
2-Naphthyl	S	Pd-on-C/CuI	THF	4	12

[a] S = 3-*pseudo*saccharyl; T = 1-phenyl-1*H*-tetrazol-5-yl. [b] The catalyst was used as such or was pre-reduced by addition of DIBAL-H as indicated. [c] Yields were determined by GC unless otherwise stated. [d] Three-fold excess of Et$_2$Zn was used. [e] Acetophenone was obtained as a side product in 22.1% yield. [f] Isolated yield. [g] Naphthalene was obtained as a minor side product.

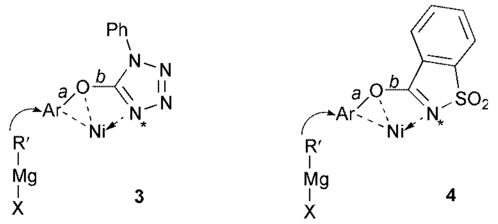
reported that cross-coupling of phenyltetrazolyl ethers **1** with alkyl or aryl Grignard reagents takes place under moderate conditions and with very short reaction times (Scheme 1; R = 1-phenyltetrazol-5-yl; R′ = alkyl, aryl; X = Br, Cl).[12] Initial reaction of NiCl$_2$(dppp) with some of the Grignard reagent generates the true Ni(0) catalyst, to which the ether **1** adds oxidatively to give complex **A**. Decomposition of this complex by more Grignard reagent R′MgX (possibly *via* intermediate **B**) leads to regeneration of the catalyst and formation of the cross-coupled product Ar–R′. The heteroaromatic ethers are thought to be specifically involved in coordination to magnesium through one of the nitrogen atoms (complex **B** in Scheme 1).



Scheme 1

To confirm the earlier observations on ethers **1**, 5-phenoxy-1-phenyl-1*H*-tetrazole (**1**; Ar = phenyl) was reacted with ethylmagnesium bromide in the presence of NiCl$_2$(dppp) in refluxing ether. All of the starting material disappeared within 25 minutes, with formation of the cross-coupled product, ethylbenzene, in 78% yield. With this confirmation of reactivity, cross-coupling of *pseudo*saccharyl ethers **2** with alkyl Grignard reagents was attempted using several different nickel or palladium catalysts (see Experimental section). Under reaction conditions similar to those used for the cross-coupling of aryloxytetrazoles **1**, the *pseudo*saccharyl ethers **2** either failed to give any of the desired cross-coupled product or did so in yields of no more than about 10%, even when the amount of catalyst was increased to 0.5 molar equivalents in relation to the ether. Changes in solvent, catalyst and general reaction conditions afforded no improvement. This lack of reactivity of ethers **2** is in significant contrast with the reactivity of ethers **1** under the same conditions.[12] The recovery of unchanged *pseudo*saccharyl ethers leads to the possibility of using the two kinds of ether for selective derivatisation in complex structures such that a phenyltetrazolyl ether **1** could be cross-coupled with a Grignard reagent but a *pseudo*saccharyl ether in the same molecule would not be affected. This selectivity was quite unexpected but leads to synthetic opportunities. As is described below, *pseudo*saccharyl ethers **2** do undergo catalysed coupling with organozinc or organotin reagents. Thus, an ether **1** may be cross-coupled with an organomagnesium halide in the presence of a *pseudo*saccharyl ether **2** and then the latter can be cross-coupled with an organozinc or an organotin reagent.

The reasons for this selectivity to organomagnesium halides are not clear. Since both ethers **1** and **2** undergo nickel-catalysed reaction with organozinc or organotin compounds, it would seem that initial addition of the ethers to Ni(0) may not cleave the C–O bond (*a* in structures **3**,**4**) but this step may be completed by the incoming organometallic reagent (Scheme 2).

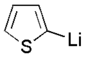


Scheme 2

From this viewpoint, the difference in nucleophilicity of the nitrogens marked with an asterisk in structures **3**,**4** may be important. The nitrogen in complexes **4** may stabilise a complex with nickel more than the corresponding nitrogen in complexes **3**, making the latter more amenable to attack by the organomagnesium halide. Semi-empirical calculations of electronic charge densities in ethers **1**,**2** show that the partial charge on the nitrogen (N*) is −0.18 for the tetrazolyl ether **1** (Ar = Ph) but is −0.60 in the *pseudo*saccharyl ether **2** (Ar = Ph). This indicates that structure **3** should be less stabilised by coordination of nickel to the nitrogen (N*) than will be the case for structure **4** (Scheme 2).

Organozinc reagents have attracted much attention.[18] They are less reactive than their magnesium counterparts towards, for example, carbonyl bonds which property, instead of being a limitation, can be very advantageous in reactions involving compounds having such functionalities. In complete contrast to their lack of reactivity with organomagnesium reagents, the *pseudo*saccharyl ethers **2** easily underwent nickel-catalysed cross-coupling with organozinc compounds. Typically, a reducing agent, such as diisobutylaluminium hydride (DIBAL-H), was added to the nickel compound used as catalyst in order to prepare nickel(0) *in situ*. Ethers **2** were cross-coupled with diethylzinc (Table 1). Palladium catalysts were found to be much less efficient.

Table 2 Cross-coupling of 5-aryloxy-1-phenyl-1*H*-tetrazoles **1** and organozinc reagents with nickel catalysts

Aryl group	Organometallic[a]	Catalyst system[b]	Solvent	Time/h	Yield[c] (%)
2-Naphthyl	$PhLi/ZnCl_2$	$Ni(acac)_2/PPh_3/BuLi$	THF	8.0	76[d]
2-Naphthyl	$PhLi/ZnCl_2$	$Ni(acac)_2/PPh_3/DIBAL$	THF	4.0	54
Phenyl	 $ZnCl_2$	$Ni(acac)_2/PPh_3/DIBAL$	THF	4.3	48[d]
4-Acetylphenyl	$PhLi/ZnCl_2$	$Ni(acac)_2/PPh_3/DIBAL$	Dioxane	4.0	61

[a] PhLi with $ZnCl_2$ gives the reagent, PhZnCl; 2-thienyl lithium with $ZnCl_2$ gives (2-thienyl)ZnCl. [b] BuLi or DIBAL are used to reduce the Ni(II) to Ni(0). [c] Yields were determined by GC unless otherwise indicated. [d] Isolated yield.

Table 3 Cross-coupling of 5-aryloxy-1-phenyl-1*H*-tetrazoles **1** or 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxides **2** (ArOR) and tetramethyltin with nickel or palladium catalysts

Ar–O–R					
Ar	R[a]	Catalyst system[b]	Solvent	Time/h	Yield (%)[c]
2-Naphthyl	S	$Pd(PPh_3)_4/LiCl$	Dioxane	23.0	48
1-Naphthyl	S	$Pd(PPh_3)_4/LiCl$	Dioxane	6.5	63
1-Naphthyl	S	$Ni(acac)_2/PPh_3/DIBAL\text{-}H$	THF	3.3	80
2,4-Dimethylpentyl	S	$Pd(PPh_3)_4/LiCl/PPh_3$	Dioxane	24.0	12
2-Naphthyl	T	$NiCl_2(dppp)/DIBAL\text{-}H$	THF	1.2	23
2-Naphthyl	T	$Ni(acac)_2/PPh_3/DIBAL\text{-}H$	THF	4.0	24

[a] S = 3-*pseudo*saccharyl; T = 1-phenyl-1*H*-tetrazol-5-yl. [b] DIBAL-H was used to reduce Ni(II) to Ni(0). [c] Yields were determined by GC.

This successful coupling of *pseudo*saccharyl ethers with organozinc reagents led to an examination of phenyltetrazolyl ethers **1** for similar cross-coupling. Under nickel-catalysed conditions, 5-aryloxytetrazoles (**1**; Ar = phenyl or 2-naphthyl) reacted equally as well with diethylzinc as did the *pseudo*saccharyl ethers **2** under similar conditions (Table 1). For both types of ether **1**,**2**, ketones could be recovered unchanged after reaction in the catalyst system. Cross-coupling of phenyltetrazolyl ethers **1** was also examined for other aryl and heteroaryl zinc compounds made *in situ*. In these cases, the other organozinc reagents reacted satisfactorily (Table 2).

In these experiments, as for the others described here, it was found that with no external reducing agent (generally DIBAL-H) no cross-coupling occurred. Replacement of DIBAL-H by *n*-butyllithium was also beneficial in the preparation of the true catalyst, Ni(0). For example, the yield of 2-phenylnaphthalene from phenylzinc chloride and 5-(2-naphthyloxy)-1-phenyl-1*H*-tetrazole increased from 54 to 76% when butyllithium was used as a prior reducing agent. Cross-coupling with 2-thienylzinc chloride indicated that heteroaromatic systems may also be used, presumably if they are less electronegative than the phenyltetrazole or saccharyl nucleofuges.

In a further series of experiments, the possibility of using the widely used organotin reagents[19] in cross-coupling with heteroaromatic ethers **1**,**2** was investigated (Table 3). Typical reaction conditions for cross-coupling with the tin reagents include nickel and palladium catalysts with DMF, dioxane or THF as solvents and lithium chloride or triphenylphosphine as a ligand exchanger. With a similar range of catalysts and reaction conditions, it appeared that the *pseudo*saccharyl ethers **2** were more amenable to cross-coupling with tetramethyltin than were the phenyltetrazolyl ethers **1**. Contrary to reports on the cross-coupling of triflates, which use palladium as catalyst for cross-coupling with tin reagents,[18,19] these results indicate that, for ethers **1**,**2**, nickel provides much the better results (Table 3). An 80% yield of 1-methylnaphthalene was obtained in the cross-coupling of 3-(2-naphthyloxy)-1λ^6,2-benzothiazole 1,1-dioxide with tetramethyltin in the presence of Ni(0) but this yield dropped to 63% with the popular tetrakis(triphenylphosphino)-palladium/LiCl combination as catalyst.

Conclusion

Phenyltetrazolyl ethers **1** cross-couple with organomagnesium, -tin and -zinc reagents but *pseudo*saccharyl ethers **2** react only with the last two. For all reactions, Ni(0) was found to be the most efficient catalyst. Pd(0) had no or very little effect for cross-coupling with organomagnesium and -zinc reagents. These results open up the possibility for selective cross-coupling. For example, palladium-catalysed cross-coupling of triflates with magnesium or zinc reagents would have little or no effect on a phenyl tetrazolyl or *pseudo*saccharyl ether but the latter could be subsequently cross-coupled under nickel-catalysed conditions. Similarly, the phenyltetrazolyl and *pseudo*saccharyl ethers may be differentiated by their reactivities towards organomagnesium halides.

Experimental

Preparation of 5-aryloxy-1-phenyl-1*H*-tetrazoles **1** and of 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxides (*pseudo*saccharyl) ethers **2** has been described.[9,10] Gas–liquid chromatograms were obtained from a "DANI 3800" gas chromatograph equipped with a flame ionisation detector and an OV-351 capillary column (25 m). Product yields were calculated by reference to an internal standard after pre-calibration and were checked by actual isolation of product.

All reactions involving organometallic species were run under argon or nitrogen and all glassware was flame-dried just before reaction or was dried in a hot oven for 24 hours and then cooled in a slow stream of argon. Unless otherwise stated, all reagents were used as purchased.

Catalysts

Dichlorobis(triphenylphosphine)nickel(II),[20] dichlorobis(diphenylphosphine)propanenickel,[21] nickel(II) acetylacetonate,[22] and tetrakis(triphenylphosphine)palladium[23] were prepared by published methods. Although no cross-coupling reactions were observed when finely divided Pd or Ni metals were intentionally added as catalysts, it cannot be ruled out that some of the process might be heterogeneous rather than homogeneous. However, solutions before and after reaction were clear.

Organometallic cross-coupling reagents

Ethylmagnesium bromide (~1.8 M),[24] methylmagnesium iodide (~1.8 M)[24] and tetramethyltin[25] were prepared by standard methods. Diethylzinc was purchased (Aldrich). Phenylzinc chloride was prepared *in situ*.[26] 2-Thienylzinc chloride was prepared in a similar manner from 2-thienyllithium and zinc chloride.

Attempted cross-coupling of 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxides 2 with Grignard reagents

In a typical reaction, $NiCl_2$(dppp) (20.3 mg; 0.037 mmol) was added to a solution of 3-phenoxy-1λ^6,2-benzothiazole 1,1-dioxide (45.1 mg; 0.17 mmol) and tridecane (internal GC standard; 25.3 mg) in diethyl ether (20 mL). The mixture was heated to reflux and a solution of ethylmagnesium bromide (3.5 mmol) was then added *via* a syringe over a period of about 10 min. Small samples of the reaction mixture (0.1 mL) were periodically extracted and quenched with hydrochloric acid. After 24 h, the yield of ethylbenzene had reached only 5.1%.

Similar experiments in other solvents (THF, DMF, dioxane) or with other catalysts ($Ni(PPh_3)_4$, $Ni(acac)_2$, $NiCl_2$(dppb), Pd/C, $PdCl_2$, and $Pd(Ph_3)_4$) or in the presence or absence of LiCl or with methylmagnesium bromide gave similar poor yields or even none of the expected cross-coupled product. A corresponding series of reactions with 2-naphthyloxy-1λ^6,2-benzothiazole 1,1-dioxide gave at best 13% of 2-ethylnaphthalene in reaction with ethylmagnesium bromide and $NiCl_2$(dppp)/LiCl as catalyst in diethyl ether.

Cross-coupling of 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxides 2 with diethylzinc in the absence of triphenylphosphine

A series of reactions was carried out, the reaction conditions and results being summarised in Table 1. In a typical reaction, diisobutylaluminium hydride (DIBAL-H; 1 M in toluene; 0.07 mL) was added to a stirred mixture of $NiCl_2$(dppp) (40.5 mg; 0.075 mmol) in THF (5 mL) to produce Ni(0) as a very fine dispersion. After about 5 min, a solution of 3-phenoxy-1λ^6, 2-benzothiazole (101.7 mg; 0.39 mmol) and tridecane (GC internal standard; 34.6 mg) in THF (15 mL) was added in one portion to the Ni(0) catalyst, followed by dropwise addition of diethylzinc (1 M in hexane; 1 mL) over a period of about 10 min. The resulting mixture was heated to reflux and small samples were extracted at intervals for examination by GC for the presence of ethylbenzene and by TLC for the presence of the starting material. After 4 h, no starting material remained and ethylbenzene had been formed in 74% yield. The experiment was repeated without DIBAL-H but gave no ethylbenzene. The remaining experiments (Table 1) were used to investigate the influences of solvent, the type of nickel complex used and the addition of triphenylphosphine to stabilise the Ni(0) formed *in situ*.

Cross-coupling of 5-aryloxy-1-phenyl-1*H*-tetrazoles 1 with diethylzinc in the presence of triphenylphosphine

In a typical reaction, DIBAL-H (1 M in toluene; 0.3 mL) was added to a mixture of $Ni(acac)_2$ (41.2 mg; 0.16 mmol) and PPh_3 (164.2 mg; 0.63 mmol) in THF (5 mL). After the mixture had turned to a black suspension (5 min), a solution of 5-(2-naphthyloxy)-1-phenyl-1*H*-tetrazole (81.2 mg; 0.28 mmol) and 1,2,4,5-tetramethylbenzene (27.4 mg) in dioxane (20 mL) was added to the reaction mixture, followed by dropwise addition over 10 min of diethylzinc (1 M, 0.5 mL). The resulting mixture was heated to reflux and small aliquots were taken periodically for GC analysis. After 4 h the yield of 2-ethylnaphthalene was 52%.

Cross-coupling of 3-aryloxy-1λ^6,2-benzothiazole 1,1-dioxides 2 with tetramethyltin

(a) In the absence of triphenylphosphine. In a typical reaction, a solution of 3-(1-naphthyloxy)-1λ^6,2-benzothiazole 1,1-dioxide (65.8 mg; 0.21 mmol) in dioxane (15 mL), was treated successively with tetramethyltin (0.4 mL; 2.9 mmol), LiCl (250 mg; 5.94 mmol), tridecane (25.6 mg), a few crystals of 2,6-di-*tert*-butyl-4-methylphenol and $Pd(PPh_3)_4$ (70 mg; 0.06 mmol). The mixture was stirred and heated under reflux. The progress of reaction was monitored by TLC. After 6.5 h, 1-methylnaphthalene was obtained in 63% yield (Table 3).

(b) In the presence of triphenylphosphine. DIBAL-H (1 M in toluene; 0.3 mL) was added to a stirred mixture of $Ni(acac)_2$ (68.3 mg; 0.22 mmol) and PPh_3 (0.7 g; 2.7 mmol) in diethyl ether (20 mL) at room temperature. After 10 min, a solution of tetramethyltin (0.3 mL; 2 mmol), 3-(1-naphthyloxy)-1λ^6,2-benzothiazole 1,1-dioxide (40.8 mg; 0.13 mmol) and tridecane (15.4 mg) in a mixture of dioxane and diethyl ether (5 : 2 v/v; 50 mL), was added over a period of 10 min and the stirred reaction mixture was then gently refluxed. After 3 h, no starting material remained and 1-methylnaphthalene had been formed in 80% yield (Table 3).

Cross-coupling of 5-(2-naphthyloxy)-1-phenyl-1*H*-tetrazoles 1 with tetramethyltin

In a typical reaction, DIBAL-H (1 M in toluene; 0.04 mL) was added to a stirred mixture of $NiCl_2$(dppp) (21.0 mg; 0.039 mmol) in diethyl ether (5 mL). A solution of 5-(2-naphthyloxy)-1-phenyl-1*H*-tetrazole (100 mg; 0.35 mmol) and tridecane (45 mg) in diethyl ether (40 mL) was added to the reaction mixture over a period of 10 min, followed by the dropwise addition of tetramethyltin (0.5 mL; 3.6 mmol) over a period of 10 min. The mixture was heated under reflux for 1.2 h to give 2-methylnaphthalene in 23% yield. Extending the reaction times did not improve the yield.

Acknowledgements

The authors are indebted to the Royal Society of Chemistry (UK), the Eschenmoser Trust and FCT (Portugal) for grants (A. F. B.).

References

1 *Comprehensive Organic Synthesis: Selectivity, Strategy and Efficiency in Modern Organic Chemistry*, eds. B. M. Trost and I. Fleming, Pergamon, Oxford, 1999, vol. 3, pp. 659–703; vol. 8, pp. 910–913.

2 A. Padwa, S. M. Sheehan and C. S. Straub, *J. Org. Chem.*, 1999, **64**, 8648.

3 P. J. Stang, M. Hanack and L. R. Subramanian, *Synthesis*, 1982, 85.

4 E. Wenkert, E. L. Michelotti and C. S. Swindell, *J. Am. Chem. Soc.*, 1979, **101**, 2246.

5 J. Y. Bae, *J. Ind. Eng. Chem.*, 1998, **4**, 319.

6 A. F. Brigas and R. A. W. Johnstone, *J. Chem. Soc., Chem. Commun.*, 1994, 1923; M. A. Huffman and N. Yasuda, *Synlett*, 1999, 471; M. E. Mower and P. DeShong, *J. Org. Chem.*, 1999, **64**, 1684; M. Rottlander and P. Knochel, *J. Org. Chem.*, 1998, **63**, 203.

7 J. A. C. Alves, J. V. Barkley, A. F. Brigas and R. A. W. Johnstone, *J. Chem. Soc., Perkin Trans. 2*, 1997, 669.

8 W. J. Musliner and J. W. Gates, *J. Am. Chem. Soc.*, 1966, **88**, 4271.

9 B. J. Hussey, R. A. W. Johnstone and I. D. Entwistle, *Tetrahedron*, 1982, **38**, 3775.

10 A. F. Brigas and R. A. W. Johnstone, *Tetrahedron Lett.*, 1990, **31**, 5789.

11 M. L. S. Cristiano, R. A. W. Johnstone and P. J. Price, *J. Chem. Soc., Perkin Trans. 1*, 1996, 1453.

12 R. A. W. Johnstone and W. N. McLean, *Tetrahedron Lett.*, 1988, **29**, 5553.

13 *Comprehensive Heterocyclic Chemistry: The Structure, Reactions, Synthesis and Uses of Heterocyclic Compounds*, vol. 5, eds. A. R. Katritzky and C. W. Rees, Pergamon Press, Oxford, 1984, ch. 4.13, pp. 834–837; J. Y. Lee, M. E. Brune, R. B. Warner, S. B. Buckner,

M. Winn, B. De, T. M. Zydowsky, T. J. Opgenorth, D. J. Kerkman and J. F. DeBernardis, *Pharmacology*, 1993, **47**, 176.
14 F. H. Allen, O. Kennard, D. G. Watson, L. Brammer, A. G. Orpen and R. Taylor, *J. Chem. Soc.*, *Perkin Trans. 2*, 1987, S1–S41.
15 J. J. P. Stewart, MOPAC 6.00, QCPE No. 455; supplied by CAChe WorksSystem v. 4.1, Oxford Molecular, Oxford Science Park, Oxford, UK OX4 4GA.
16 R. A. W. Johnstone, A. H. Wilby and I. D. Entwistle, *Chem. Rev.*, 1985, **85**, 129; J. Q. Yu and J. B. Spencer, *Chem. Eur. J.*, 1999, **5**, 2237.
17 J. C. Bayon, C. Claver and A. M. MasdeuBulto, *Coord. Chem. Rev.*, 1999, **195**, 73; T. Hiyama, H. Matsuhashi, A. Fujita, M. Tanaka, K. Hirabayash, M. Shimizu and A. Mori, *Organometallics*, 1996, **15**, 5762.
18 M. Kimura, I. Kiyama, T. Tomizawa, Y. Horino, S. Tanaka and Y. Tamaru, *Tetrahedron Lett.*, 1999, **40**, 6795; M. Chavarot and Z. Pikramenou, *Tetrahedron Lett.*, 1999, **40**, 6865; T. Shiota and T. Yamamori, *J. Org. Chem.*, 1999, **64**, 453; M. Okano, M. Amano and K. Takagi, *Tetrahedron Lett.*, 1998, **39**, 3001.
19 W. Shen and L. Wang, *J. Org. Chem.*, 1999, **64**, 8873; E. Antonelli, P. Rosi, C. LoSterzo and E. Viola, *J. Organomet. Chem.*, 1999, **578**, 210; A. Dondoni, C. Ghiglione, A. Marra and M. Scoponi, *J. Org. Chem.*, 1998, **63**, 9535.
20 L. Zhu, R. M. Wehmeyer and R. D. Rieke, *J. Org. Chem.*, 1991, **56**, 1445.
21 G. R. van Hecke and W. de W. Horrocks, *Inorg. Chem.*, 1966, **5**, 1968.
22 R. G. Charles and M. A. Pawlikowski, *J. Am. Chem. Soc.*, 1958, **62**, 440.
23 G. Booth, in *Advances in Inorganic Chemistry and Radiochemistry*, vol. 6, eds. H. J. Emeléus and A. G. Sharpe, Academic Press, New York, 1964, pp. 1–69.
24 A. Vogel, *Textbook of Practical Organic Chemistry*, 4th edn., revisers, B. S. Furniss, A. J. Hannaford, V. Rogers, P. W. G. Smith and A. R. Tatchell, Longman, London, 1978, pp. 363–366.
25 W. F. Edgell and C. D. Ward, *J. Am. Chem. Soc.*, 1954, **76**, 1169.
26 G. P. Roth and C. E. Fuller, *J. Org. Chem.*, 1991, **56**, 3493.