On the 'Novel two-phase oxidative cross-coupling of the two-component molecular crystal of 2-naphthol and 2-naphthylamine'[1]

Štěpán Vyskočil,*[a,b] Martin Smrčina,[a] Miroslav Lorenc,[a] Vladimír Hanuš,[c] Miroslav Polášek[c] and Pavel Kočovský*[b]†

[a] *Department of Organic Chemistry, Charles University, 128 40, Prague 2, Czech Republic*
[b] *Department of Chemistry, University of Leicester, Leicester, UK LE1 7RH*
[c] *J. Heyrovský Institute of Physical Chemistry, Academy of Sciences of the Czech Republic, 182 23 Prague 8, Czech Republic*

The $FeCl_3$-mediated, heterogeneous cross-coupling of the title compounds ($1 + 2 \rightarrow 3$) has been re-examined and formation of the molecular crystal ($1 + 2$) shown to be irrelevant to the selectivity observed; a comparison of Fe^{III} and Cu^{II} as reagents is presented.

Oxidative self-coupling of 2-naphthol **1** is a well known reaction; the resulting BINOL **4** constitutes a pivotal intermediate in the synthesis of numerous chiral ligands, such as BINAP and MOP.[2] A number of mild oxidants have been reported to effect this coupling, in particular Cu^{II}, Fe^{III} and Mn^{III} salts.[3]

In a recent paper, Ding *et al.*[1] reported on the Fe^{III}-mediated, two-phase oxidative cross-coupling of the title compounds to produce (±)-2-amino-2′-hydroxy-1,1′-binaphthyl (NOBIN) (**1** + **2** → **3**, Scheme 1) and rationalised this outcome as being due to the unique formation of the molecular crystal **1** + **2** prior to the reaction. We challenge this communication for the following reasons. Firstly, in 1991, we had published the very same cross-coupling (**1** + **2** → **3**), mediated by Cu^{II} in a methanolic solution,[4,5] which demonstrates that this selectivity is not exclusive to the heterogeneous system. Secondly, this is not the only case of a highly selective cross-coupling; there are about twenty examples of this kind known to date which all occur in a homogeneous solution.[4–8] Thirdly, Ding's mechanism[1] is in conflict with that proposed by us.[6] Here we present a direct comparison of Ding's protocol with our published procedure and offer evidence which does not support the mechanism proposed by Ding.

We have shown that 2-naphthol **1** and 2-naphthylamine **2** can be cross-coupled by treatment with a complex generated *in situ* from $CuCl_2$ and an amine, such as $BnNH_2$ or Bu^tNH_2; in a methanolic solution and under anaerobic conditions, the resulting NOBIN **3** is obtained in up to 85% yield. As by-products, we have detected the diol **4** (6%) and diamine **5** (2%). The presence of an amine is crucial for high conversion and selectivity;[4–7] if a chiral amine is employed, acceptable enantioselectivity is attained (46% ee in the case of **3** and up to ≥99% ee for **4**).[5]

In contrast to the previous experiments, which were carried out in homogeneous solutions,[3–8] Ding *et al.*[1] used a suspension of the pre-formed mixture of **1** and **2** in water and $FeCl_3$ as the oxidant. At 55 °C the conversion was practically quantitative and the yields fo **3** were in the range of 71–82% in typical instances; **4** (13–19%) was identified as the only by-product, while **5** was not detected.

We have rationalised the striking preference for the cross-coupling as follows: in the pair to be cross-coupled, one partner has to be prone to a ready, one-electron oxidation (as documented by cyclic voltammetry and *ab initio* calculations) and the other should be capable of trapping the radical-like species thus generated;[6‡] the coupling itself apparently occurs in the co-ordination sphere of the metal (*vide infra*).[5b,6,8d,8e] If the redox potentials of the two partners differ sufficiently (as is the case for **1** and **2** and several other combinations), high preference for the cross-coupling can be anticipated. On the other hand, if the latter difference is small, the reaction becomes non-selective and mixtures of cross- and self-coupled products are obtained.[6] Ding *et al.* proposed a different mechanism, according to which **1** and **2** form a molecular crystal (or a molecular compound) and the coupling occurs either in the solid state or at the boundary between the solid and liquid phases.[1] The favourable orientation of **1** and **2** in the latter crystal is then assumed to control the coupling reaction to produce mainly **3**, whereas the self-coupling processes, which would lead to **4** and **5**, are suppressed.[1]

Ding's molecular crystal (or compound) is, presumably, formed as a result of interaction of a weak Brønsted acid **1** with a weak base **2**. Therefore, the differences in the IR spectra and in the powder X-ray diffraction characteristics he reported for the crystal and the individual components[1] are not unexpected.§

In a typical experiment, carried out with a suspension of the molecular crystal in an aqueous solution of $FeCl_3$ at 55 °C, high preference for the cross-coupling was observed (82% of **3** and 14% of **4**),¶ which was interpreted by Ding as evidence for the crucial role of the molecular crystal in controlling the chemoselectivity.[1] On the other hand, when solid **1** and **2** were added separately to an aqueous solution of $FeCl_3$ at 55 °C, very similar selectivity was observed (78% of **3** and 20% of **4**).[1] To account for this result, Ding suggested a rapid formation of the molecular crystal prior to the coupling.[1**]

We find little support for the proposed mechanism on the grounds of the experiments[1] presented. First of all, neither **1** nor **2** is entirely insoluble in water: 1 g of **1** is dissolved in 1 l of water at ambient temperature, while the same amount will dissolve in 80 ml of boiling water.[9] According to our experience, the solubility of **2** is similar to that of **1**.†† Hence, appreciable amounts of each of **1** and **2** must be dissolved under the reaction conditions both at room temp. and, especially, at 55 °C. This alone casts doubts on Ding's mechanism and suggests that the oxidative coupling does, in fact, occur in the aqueous phase and is controlled by the factors[6] we have identified. Furthermore, Ding observed a loss of selectivity when $FeCl_3$ was replaced by other Fe^{III} salts, namely $Fe_2(SO_4)_3$ or NH_4FeCl_4, as oxidants. We believe this is further in conflict

1 X = OH
2 X = NH₂

3 X = OH, Y = NH₂
4 X = OH, Y = OH
5 X = NH₂, Y = NH₂
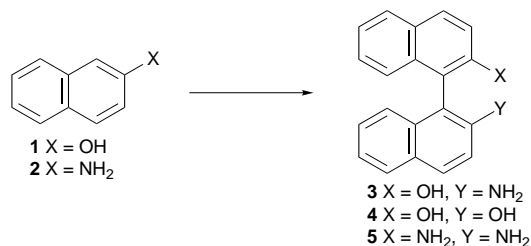
Scheme 1

with Ding's hypothesis. Should the selectivity originate from the molecular crystal, the nature of the metal ligands would be irrelevant.‡‡

To address these issues, we have carried out the following experiment: equimolar amounts of **1** and **2** were dissolved in CH_2Cl_2 and stirred vigorously with an aqueous solution of $FeCl_3$ at room temp. for 48 h. With this two-phase system we obtained similar selectivity to that reported by Ding¶‖ (the ratio of **3**, **4** and **5** was 79 : 9 : 12, as revealed by GC), although the conversion (*ca.* 50%) was not as high, presumably owing to the lower temperature and the lower concentration of the reactants in the aqueous phase in our case.

In conclusion, we have shown that the cross-coupling of **1** and **2**, suspended in an aqueous solution of $FeCl_3$, most likely occurs in solution (note that the reactants are sparingly soluble in water). The selectivity observed does not originate from the existence of the molecular crystal and can be attributed to the different redox properties of the reaction partners, as proposed earlier by us.[6] Since the product **3** is much less soluble than the reactants, its formation siphons off the reactants from the solution and the system obeys the Le Chatelier–Braun principle. Under these conditions, BINOL **4** is the main contaminant. When carried out in a methanolic solution with Cu^{II}, less BINOL is formed but some diamine **5** can be detected (*vide supra*).[6] These marginal differences between the two methods are presumably associated with the nature of the oxidant (Fe *vs.* Cu) rather than with the homogeneity or non-homogeneity of the reaction mixture. Carrying out the reaction in aqueous suspension appears to have the advantage of simplicity if racemic NOBIN **3** is required. However, its asymmetric verison remains to be developed if this method is to be competititve with the homogeneous protocol. The same conclusion holds for the synthesis of BINOL **4** by the self-coupling of **1**.

Notes and References

† E-mail: pk10@le.ac.uk

‡ Ding *et al.* [ref. 3(*k*)] proposed an analogous mechanism for the self-coupling of **1** to give **4** after our original communication (ref. 6).

§ Ding has reported the following IR peaks: **1**, 3250; **2**, 3375, 3290, 3170; **1** + **2**, 3350, 3260 cm⁻¹. Our values (obtained in substance by means of the 'Golden Gate' technique) were as follows: **1**, 3197; **2**, 3390, 3302, 3197; **1** + **2**, 3363, 3275 cm⁻¹ (or 3364, 3357 sh, 3283 cm⁻¹ for a suspension of the latter mixture in fluorolube). On the other hand, a 10^{-3} M solution of the mixture in CCl_4 represented a clear superposition of the spectra of the two components. All this indicates a strong intermolecular hydrogen bonding between **1** and **2** in the solid state, which disappears on dissolving in a nonpolar solvent; therefore, selective pairing in protic solvents, such as water or alcohols, is unlikely.

¶ A rigorous, quantitative interpretation of Ding's experiments is difficult. Based on the HPLC analysis, he claimed to obtain **3** (82%) and **4** (14%) at 100% consumption of **1**. Since *two* molecules of **1** are required to form **4**, these yields would appear to be impossible since the total would exceed 100% (see note ‖).

‖ We have repeated Ding's experiment. A capillary GC (using a DB5 column, 15 m × 0.5 mm, at 220 °C) with FID gave a 90 : 8 : 2 ratio of **3**, **4** and **5** in the crude product.

** In this instance, the molecular crystal is presumably formed in an equilibrium process that involves partial dissolving of each of the components and crystallisation of the less soluble molecular crystal.

†† Note that both **1** and **2** can be purified by crystallisation from hot water.

‡‡ The ligands' crucial role is further evidenced by asymmetric induction, observed in the presence of enantiopure amines (ref. 5). Moreover, this effect indicates that the coupling does occur in the co-ordination sphere of the metal (or, at least, in its vicinity) (ref. 5), rather than *via* a free-radical species. For details and further discussion, see refs. 5(*b*), 8(*d*) and 8(*e*).

1 K. Ding, Q. Xu, Y. Wang, J. Liu, Z. Yu, B. Du, Y. Wu, H. Koshima and T. Matsuura, *Chem. Commun.,* 1997, 693.

2 For reviews, see: C. Rosini, L. Franzini, A. Raffaelli and P. Salvadori, *Synthesis,* 1992, 503; R. Noyori, *Asymmetric Catalysis in Organic Synthesis*, Wiley, New York, 1994; T. Hayashi, *Acta Chem. Scand.,* 1996, **50**, 259.

3 Cu^{II}: (*a*) B. Ferringa and H. Wynberg, *Tetrahedron Lett.,* 1977, 4447; (*b*) B. Ferringa and H. Wynberg, *Bioorg. Chem.,* 1978, **7**, 397; (*c*) K. Kushioka, *J. Org. Chem.,* 1983, **48**, 4948; (*d*) K. Yamamoto, H. Fukushima and M. Nakazaki, *J. Chem. Soc., Chem. Commun.,* 1984, 1490; (*e*) J. Brussee, J. L. G. Groenendijk, J. M. te Koppele and A. C. A. Jansen, *Tetrahedron,* 1985, **41**, 3313; (*f*) T. Sakamoto, H. Yonehara and C. Pac, *J. Org. Chem.,* 1994, **59**, 6859. Cu^{II}/O_2: (*g*) M. Noji, M. Nakajima and K. Koga, *Tetrahedron Lett.,* 1994, **35**, 7983; (*h*) B. H. Lipshutz, B. James, S. Vance and I. Carrico, *Tetrahedron Lett.,* 1997, **38**, 753. Fe^{III}: (*i*) R. Pummerer and A. Rieche, *Chem. Ber.,* 1926, 59; (*j*) F. Toda, K. Tanaka and S. Iwata, *J. Org. Chem.,* 1989, **54**, 3007 and references cited therein; (*k*) K. Ding, Y. Wang, L. Zhang, Y. Wu and T. Matsuura, *Tetrahedron,* 1996, **52**, 1005. Mn^{III}: (*l*) M. J. S. Dewar and T. Nakaya, *J. Am. Chem. Soc.,* 1968, **90**, 7134; (*m*) K. Yamamoto, H. Fukushima, Y. Okamoto, K. Hatada and M. Nakazaki, *J. Chem. Soc., Chem. Commun.,* 1984, 1111; (*n*) F. Diederich, M. R. Hester and M. Uyeki, *Angew. Chem., Int. Ed. Engl.,* 1988, **27**, 1705. Other methods involve melting the reactant or ball-milling in the presence of $FeCl_3.6H_2O$: (*o*) J. Bao, W. D. Wulff, J. B. Dominy, M. J. Fumo, E. B. Grant, A. C. Rob, M. C. Whitcomb, S. M. Yeung, R. L. Ostrander and A. L. Rheingold, *J. Am. Chem. Soc.,* 1996, **118**, 3392; (*p*) M. O. Rasmussen, O. Axelson and D. Tanner, *Synth. Commun.,* 1997, **27**, 4027.

4 M. Smrčina, M. Lorenc, V. Hanuš and P. Kočovský, *Synlett,* 1991, 231.

5 (*a*) M. Smrčina, M. Lorenc, V. Hanuš, P. Sedmera and P. Kočovský, *J. Org. Chem.,* 1992, **57**, 1917; (*b*) M. Smrčina, J. Poláková, Š. Vyskočil and P. Kočovský, *J. Org. Chem.,* 1993, **58**, 4534.

6 M. Smrčina, Š. Vyskočil, B. Máca, M. Polášek, T. A. Claxton, A. P. Abbott and P. Kočovský, *J. Org. Chem.,* 1994, **59**, 2156.

7 M. Smrčina, Š. Vyskočil, J. Polívková, J. Poláková and P. Kočovský, *Collect. Czech. Chem. Commun.,* 1996, **61**, 1520.

8 (*a*) K. Yamamoto, H. Yumioka, Y. Okamoto and H. Chikamatsu, *J. Chem. Soc., Chem. Commun.,* 1987, 168; (*b*) M. Hovorka, J. Günterová and J. Závada, *Tetrahedron Lett.,* 1990, **31**, 413; (*c*) M. Hovorka and J. Závada, *Org. Prep. Proceed. Int.,* 1991, **23**, 200; (*d*) M. Hovorka, J. Ščigel, J. Günterová, M. Tichý and J. Závada, *Tetrahedron,* 1992, **48**, 9503; (*e*) M. Hovorka and J. Závada, *Tetrahedron,* 1992, **48**, 9517.

9 *The Merck Index*, 12th edn., Merck & Co., Inc., Whitehouse Station, NJ, 1996, p. 1096.