ChemComm

RSC Publishing

COMMUNICATION

View Article Online
View Journal

A dinuclear ruthenium catalyst with a confined cavity: selectivity in the addition of aliphatic carboxylic acids to phenylacetylene†

Cite this: DOI: 10.1039/c2cc38454j

Received 4th September 2012,
Accepted 3rd December 2012

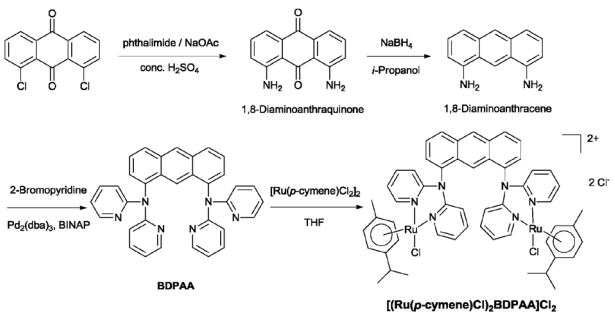
DOI: 10.1039/c2cc38454j

www.rsc.org/chemcomm

Kwong-Chak Cheung,‡ Wing-Leung Wong,‡ Ming-Him So, Zhong-Yuan Zhou, Siu-Cheong Yan and Kwok-Yin Wong*

A dinuclear ruthenium catalyst with a rigid anthracene spacer shows excellent regio- and stereo-selectivity in the atom-economic addition of aliphatic carboxylic acids to phenylacetylene, producing exclusively anti-Markovnikov enol-esters with high *E*/*Z* ratios of the isomers.

The development of selective catalysts for atom-economic reactions is important, as these reactions give the desired products without by-products or wastes.[1] In recent years, ruthenium catalysts have become attractive for applications in atom-economic reactions,[2,3] in particular the activation of unsaturated hydrocarbon molecules for selective carbon–heteroatom bond formation.[4] Since the first report by Rotem and Shvo,[5] a variety of efficient ruthenium catalysts has been developed for the addition of carboxylic acids to terminal alkynes.[6–9] The development of this organic transformation is dominated by mononuclear ruthenium–phosphine catalysts: good regioselectivity is usually achieved with a combination of a ruthenium precursor and appropriate phosphine ligands, though the use of dinuclear ruthenium complexes have also been reported.[5,9] Depending on the ligands, the ruthenium catalysts are known to promote the electrophilic activation of alkynes *via* either the classical Markovnikov or the anti-Markovnikov addition reactions. For the anti-Markovnikov products, the *Z*-enol esters are usually the preferred isomer.[10] Selective preparation of *E*-enol ester using ruthenium catalysts, however, is still a challenge.[11] We report here, to the best of our knowledge, the first example of a dinuclear ruthenium catalyst with *N*-donor dipyridylamine ligands and its characteristic production of *E*-enol esters as the major product in the catalytic anti-Markovnikov transformation of phenylacetylene.



Scheme 1 Synthetic route to the dinuclear ruthenium complex.

A synthetic route to the new dinuclear ruthenium complex is outlined in Scheme 1. The ligand 1,8-bis(2,2-dipyridylamino) anthracene (**BDPAA**) was constructed to provide a rigid anthracene spacer for the two dipyridylamine units[12] at its 1,8 positions, respectively, each of which then coordinated to one ruthenium metal.

The X-ray structure§ of the dinuclear complex $[(Ru(p\text{-cymene})Cl)_2\mathbf{BDPAA}](CF_3SO_3)_2$ is shown in Fig. 1(A). Two $Ru^{II}(p\text{-cymene})Cl$ moieties independently coordinated with the 2,2′-dipyridylamine moiety, which are attached covalently at the 1,8-position of the anthracene spacer. The two *p*-cymenes coordinated with the two ruthenium centers, respectively, are located at the outer sides of the complex. The short bond distances of Ru–cymene (approximately 2.2 Å) indicate the strong coordination between the ruthenium metals and cymene ligands. In contrast, the two chloro ligands (Ru(1)–Cl(1) and Ru(2)–Cl(2) $\approx$ 2.4 Å) are found to be pointing towards each other in the center position of the dinuclear complex. Due to the rigidity of the anthracene spacer, a confined cavity is created between the two ruthenium centers, with an estimated distance of about 9.2 Å for Ru(1)–Ru(2).

The active catalyst was prepared by replacing the chloride ligands in $[(Ru(p\text{-cymene})Cl)_2\mathbf{BDPAA}]^{2+}$ with the more labile triflate ligand by treatment with $AgCF_3SO_3$ in methanol to give $[(Ru(p\text{-cymene})CF_3SO_3)_2\mathbf{BDPAA}]^{2+}$ (**1**), which effectively catalyzed

Department of Applied Biology and Chemical Technology and the State Key Laboratory of Chirosciences, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong, China. E-mail: kwok-yin.wong@polyu.edu.hk; Fax: +852 2364-9932; Tel: +852 3400-3977

† Electronic supplementary information (ESI) available: Detailed synthetic procedures, characterizations, conditions for catalysis, and X-ray data. CCDC 899405 and 899406. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2cc38454j

‡ These authors contributed equally to this work.

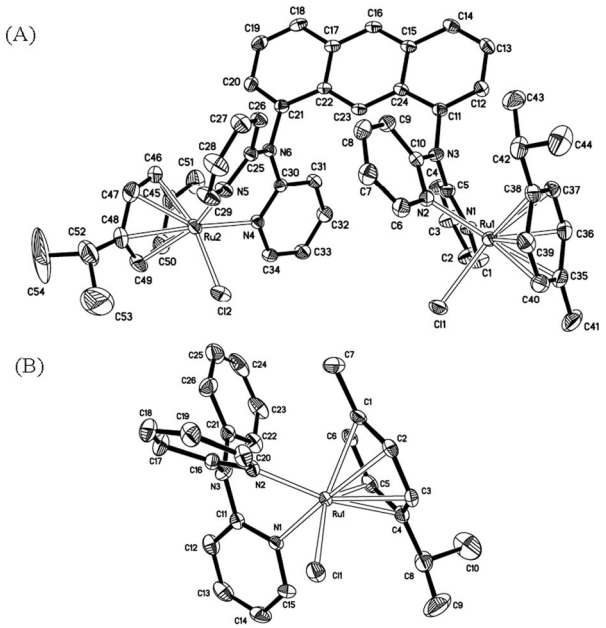
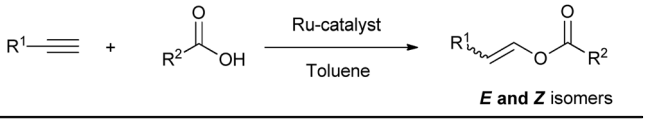


Fig. 1 The X-ray crystal structures: (A) a dinuclear $[(Ru(p\text{-cymene})Cl)_2\mathbf{BDPAA}]^{2+}$ complex. (30% probability level for the ellipsoids; two triflate anions ($CF_3SO_3^-$), one CH_3CN solvent molecule, and hydrogen atoms are not shown for clarity); (B) a mononuclear $[(Ru(p\text{-cymene})Cl)\mathbf{DPPA}]^+$ complex. (30% probability level for the ellipsoids; one chloride counterion (Cl^-), one H_2O solvent molecule, and hydrogen atoms are not shown for clarity).

Table 1 The investigation of stereoselectivity in the Ru-catalyzed addition of carboxylic acids to phenylacetylene: catalyst **1** = dinuclear Ru-complex, catalyst **2** = mononuclear Ru-complex[a]



					Stereoselectivity[c]	
Entry	Catalyst	R^1	R^2	Yield[b]/%	*E*	Z
1	**1**	Ph	CH_3	95	6.5	1
2	**1**	Ph	$n\text{-}C_2H_5$	93	9.3	1
3	**1**	Ph	$n\text{-}C_3H_7$	93	11	1
4	**1**	Ph	$n\text{-}C_4H_9$	92	9.6	1
5	**1**	Ph	$n\text{-}C_5H_{11}$	91	10	1
6	**1**	Ph	$n\text{-}C_6H_{13}$	81	3	1
7[d]	**1**	Ph	Ph	85	1	1.2
8[d]	**1**	$n\text{-}C_6H_{13}$	Ph	60	1	1.4
9[d]	**1**	$n\text{-}C_6H_{13}$	$n\text{-}C_3H_7$	75	1	1.3
10	**2**	Ph	CH_3	95	1	1.5
11	**2**	Ph	$n\text{-}C_2H_5$	95	1	1.6
12	**2**	Ph	$n\text{-}C_3H_7$	95	1	1.2
13	**2**	Ph	$n\text{-}C_4H_9$	94	1	1.3
14	**2**	Ph	$n\text{-}C_5H_{11}$	94	1	1.2
15	**2**	Ph	$n\text{-}C_6H_{13}$	92	1	1.3
16[d]	**2**	Ph	Ph	90	1	1.7
17[d]	**2**	$n\text{-}C_6H_{13}$	Ph	96	1	1.5
18[d]	**2**	$n\text{-}C_6H_{13}$	$n\text{-}C_3H_7$	90	1	1.1

[a] Reaction conditions: phenylacetylene (1 mmol), catalyst 4 mol%, carboxylic acid (1.2 equivalents) in dry toluene (2.5 ml) under nitrogen at 85 °C for 24 h. [b] Yield of enol-esters was determined by GC-MS based on 1 mmol phenylacetylene. [c] Stereoselectivity was estimated by GC-MS. [d] Reaction was performed at 120 °C.

the formation of enol esters in good yields. The result of the addition reactions and stereoselectivity are summarized in Table 1.[13]

The experimental results demonstrate that the dinuclear catalyst **1** produces anti-Markovnikov enol esters exclusively in 100% regioselectivity. In all cases examined in the catalysis, no *gem*-enol ester was observed. Moreover, as clearly indicated by the high isomer ratio of $E/Z = 6.5$ with acetic acid (Table 1, entry 1), the stereoselectivity of catalyst **1** was found to be much more favorable for *E*-enol ester formation than the *Z*-isomer.

To understand more on the stereoselectivity of the dinuclear catalyst for *E*-enol ester production, aliphatic carboxylic acids of different chain lengths were examined. The stereoselectivity was obviously improved as the chain length of the carboxylic acid was increased (Table 1, entries 1–3). In the case of propanoic acid, the *E*/*Z* ratio is significantly increased to 9.3, which is a very high stereoselectivity found in ruthenium-catalyzed addition of carboxylic acids to phenylacetylene.[5–11] The *E*/*Z* ratio was further enhanced with butanoic acid (entry 3: $E/Z = 11$) whereas the yield remained as good as acetic acid (95%) and propanoic acid (93%). However, when pentanoic acid or hexanoic acid was used in the reactions, the *E*/*Z* ratio dropped to about 10 (entries 4 and 5). In the case of heptanoic acid, the stereoselectivity dropped significantly ($E/Z = 3$) and the yield decreased to 81%, which is much lower than those shorter chained carboxylic acids (entry 6). When benzoic acid was tested, the catalytic results indicated that both the yields and stereoselectivity of the adduct were poor (entry 7). The reaction of 1-octyne with butanoic acid and benzoic acid was also investigated with **1** as the catalyst. The reaction gave moderate yields (60–75%) but no stereoselectivity towards the *E*-isomer was observed (entries 8 and 9).

In order to understand more about the stereochemistry of the dinuclear ruthenium complex in the catalysis, its mononuclear analogue, $[(Ru(p\text{-cymene})Cl)\mathbf{DPPA}]^+$ (**DPPA** = *N*,*N*-di(2-pyridyl)-phenylamine), was also synthesized and investigated for comparison. The X-ray structure of $[(Ru(p\text{-cymene})Cl)\mathbf{DPPA}]^+$ is shown in Fig. 1(B). In general, the mononuclear $[(Ru(p\text{-cymene})(CF_3SO_3)\mathbf{DPPA}]^+$ complex (**2**) exhibits similar yields (92–95%) but much poorer stereoselectivity compared to the dinuclear complex in the catalysis. It is worthy to note that the mononuclear catalyst **2** gives both *Z*- and *E*-isomers, with the *Z*-isomer slightly predominant with regard to the *E*-isomer in the catalysis (Table 1, Z/E ratio = 1.1–1.7).

Based on the X-ray structure of $[(Ru(p\text{-cymene})Cl)_2\mathbf{BDPAA}]^{2+}$, the space between the two ruthenium centers was estimated to be about 9.2 Å. This confined space is not large enough to accommodate two ruthenium phenylethenylidene species[14] because the active sites are facing each other in the cavity. In contrast, the cavity is a good fit to hold two molecules of carboxylic acids for the reaction. Therefore, it is more favourable for the ruthenium phenylethenylidene species to orient in such a manner that the phenylethenylidenes are pointing out of the cavity (Fig. 2) to give the *E*-enol ester exclusively in the catalysis. This can explain why stereoselectivity towards the *E*-isomer was only observed for phenylacetylene but not 1-octyne. Nevertheless, the pathway with one phenylethenylidene pointing towards the cavity (pathway B in Fig. S1, ESI†), though less favorable, can still

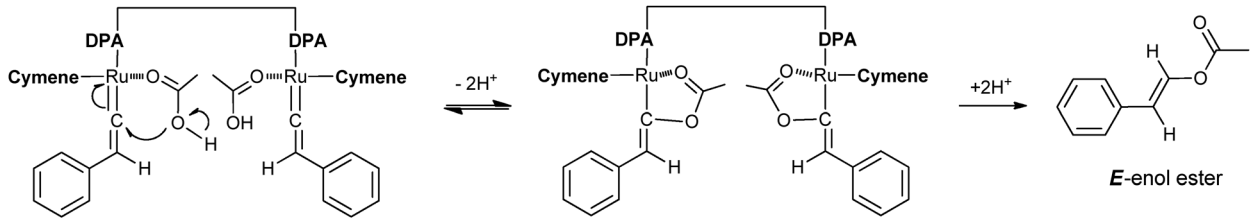


Fig. 2 A possible mechanism for the dinuclear ruthenium catalyst to produce the *E*-enol ester in the catalysis (**DPA** = 2,2′-dipyridylamine unit; spacer = anthracene connected to the two **DPA** units at the 1,8-position).

occur to produce a mixture of *Z* and *E*-enol esters. In the case of the mononuclear ruthenium catalyst, the phenyl ring of the ruthenium phenylethenylidene species encounters least steric hindrance when it is furthest away from the cymene group (pathway D in Fig. S1, ESI†). This orientation of the ruthenium phenylethenylidene species leads to the more favourable production of *Z*-enol esters in the catalysis. The ruthenium phenylethenylidene intermediates can be detected by ESI-MS and ^{13}C NMR. A broad low-field resonance signal of the ruthenium carbene species appears at $\delta \sim 199$ ppm (Fig. S6 and S7 in ESI†) which is similar to those reported in the literature ($\delta \sim 200$ ppm).[15] The ruthenium phenylethenylidene species of **1** and **2** were also observed in the mass spectra (Fig. S8 and S9, ESI†) after reaction with phenylacetylene in solution. The mass spectrum of the dinuclear complex confirmed the formation of two ruthenium phenylethenylidene moieties in the same molecule (Fig. S9, ESI†).

In conclusion, we have demonstrated that a dinuclear ruthenium complex with a confined cavity can be a selective catalyst in the atom-economic addition of aliphatic carboxylic acid to phenylacetylene to give exclusively the anti-Markovnikov enol esters with favourable *E*/*Z* stereoisomer ratios.

We acknowledge the support of the Hong Kong Polytechnic University, the Innovation and Technology Commission, the Research Grants Council (PolyU 5015/07P) and the Special Equipment Grant (SEG_PolyU01) of the University Grants Committee.

Notes and references

§ Selected crystal data for [(Ru(*p*-cymene)Cl)$_2$**BDPAA**](CF$_3$SO$_3$)$_2$: formula = $Ru_2Cl_2(C_{54}H_{52}N_6)\cdot CH_3CN\cdot(CF_3SO_3)_2$; M = 1397.25; monoclinic; $P2(1)/c$; a = 16.2205(2), b = 14.5792(2), c = 25.0080(3) Å; β = 95.4810(10)°; V = 5886.90(13) Å^3; T = 296(2) K; Z = 4; μ = 0.750 mm^{-1}; reflections collected = 50 320; independent reflections = 13 291 (R_{int} = 0.0488); final R values [$I > 2\sigma(I)$]: R_1 = 0.0550, wR_2 = 0.1520; final R values (all data): R_1 = 0.0884, wR_2 = 0.1699.

Selected crystal data for [(Ru(*p*-cymene)Cl)**DPPA**](Cl): formula = [RuCl($C_{26}H_{27}N_3$)]Cl·1.5(H_2O); M = 580.50; monoclinic; $C2/c$; a = 17.8467(3), b = 19.9586(4), c = 14.4679(3) Å; β = 93.8880(10)°; V = 5141.53(17) Å^3; T = 296(2) K; Z = 8; μ = 0.844 mm^{-1}; reflections collected = 40 721; independent reflections = 5888 (R_{int} = 0.0572); final R values [$I > 2\sigma(I)$] R_1 = 0.0389, wR_2 = 0.1150; R values (all data) R_1 = 0.0488, wR_2 = 0.1300.

1 R. A. Sheldon and R. S. Downing, *Appl. Catal., A*, 1999, **189**, 163–183.
2 B. M. Trost, F. D. Toste and A. B. Pinkerton, *Chem. Rev.*, 2001, **101**, 2067–2096.
3 B. M. Trost and M. J. Krische, *Synlett*, 1998, 1–16.
4 C. Bruneau and P. H. Dixneuf, *Metal vinylidenes and allenylidenes in catalysis: from reactivity to applications in synthesis*, Wiley-VCH, Weinheim, 2008.
5 M. Rotem and Y. Shvo, *Organometallics*, 1983, **2**, 1691–1692.
6 For recent reviews, see: (*a*) M. Beller, J. Seayad, A. Tillack and H. Jiao, *Angew. Chem., Int. Ed.*, 2004, **43**, 3368–3398; (*b*) R. Drozdzak, B. Allaert, N. Ledoux, I. Dragutan, V. Dragutan and F. Verpoort, *Adv. Synth. Catal.*, 2005, **347**, 1721–1743; (*c*) C. Bruneau and P. H. Dixneuf, *Angew. Chem., Int. Ed.*, 2006, **45**, 2176–2203; (*d*) L. J. Gooßen, N. Rodríguez and K. Gooßen, *Angew. Chem., Int. Ed.*, 2008, **47**, 3100–3120.
7 (*a*) M. Nishiumi, H. Miura, K. Wada, S. Hosokawa and M. Inoue, *Adv. Synth. Catal.*, 2010, **352**, 3045–3052; (*b*) S. T. Tan and W. Y. Fan, *Eur. J. Inorg. Chem.*, 2010, 4631–4635; (*c*) S. Karabulut, B. Ö. Öztürk and Y. Imamoğlu, *J. Organomet. Chem.*, 2010, **695**, 2161–2166; (*d*) V. Cadierno, J. Francos and J. Gimeno, *Organometallics*, 2011, **30**, 852–862; (*e*) M. Kawatsura, J. Namioka, K. Kajita, M. Yamamoto, H. Tsuji and T. Itoh, *Org. Lett.*, 2011, **13**, 3285–3287; (*f*) S. Saha, T. Ghatak, B. Saha, H. Doucet and J. K. Bera, *Organometallics*, 2012, **31**, 5500–5505; (*g*) U. K. Das and M. Bhattacharjee, *J. Organomet. Chem.*, 2012, **700**, 78–82.
8 (*a*) M. Nishiumi, H. Miura, K. Wada, S. Hosokawa and M. Inoue, *ACS Catal.*, 2012, **2**, 1753–1759; (*b*) T. Opstal and F. Verpoort, *Synlett*, 2002, 935–941.
9 (*a*) M. Rotem and Y. Shvo, *J. Organomet. Chem.*, 1993, **448**, 189–204; (*b*) C. Bruneau, Z. Kabouche, M. Neveux, B. Seiller and P. H. Dixneuf, *Inorg. Chim. Acta*, 1994, **222**, 154–163; (*c*) C. Darcel, C. Bruneau, P. H. Dixneuf and G. Neef, *J. Chem. Soc., Chem. Commun.*, 1994, 333–334; (*d*) S. Ye and W. K. Leong, *J. Organomet. Chem.*, 2006, **691**, 1216–1222.
10 (*a*) H. Doucet, J. Höfer, C. Bruneau and P. H. Dixneuf, *Chem. Commun.*, 1993, 850–851; (*b*) C. Bruneau and P. H. Dixneuf, *Chem. Commun.*, 1997, 507–512; (*c*) H. Kawano, Y. Masaki, T. Matsunaga, K. Hiraki, M. Onishi and T. Tsubomura, *J. Organomet. Chem.*, 2000, **601**, 69–77; (*d*) K. Melis and F. Verpoort, *J. Mol. Catal. A: Chem.*, 2003, **194**, 39–47; (*e*) L. J. Goossen, J. Paetzold and D. Koley, *Chem. Commun.*, 2003, 706–707; (*f*) R. Hua and X. Tian, *J. Org. Chem.*, 2004, **69**, 5782–5784; (*g*) S. Doherty, J. G. Knight, R. K. Rath, W. Clegg, R. W. Harrington, C. R. Newman, R. Campbell and H. Amin, *Organometallics*, 2005, **24**, 2633–2644; (*h*) P. Pelagatti, A. Bacchi, M. Balordi, S. Bolaño, F. Calbiani, L. Elviri, L. Gonsalvi, C. Pelizzi, M. Peruzzini and D. Rogolino, *Eur. J. Inorg. Chem.*, 2006, 2422–2436; (*i*) Q. Willem, F. Nicks, X. Sauvage, L. Delaude and A. Demonceau, *J. Organomet. Chem.*, 2009, **694**, 4049–4055; (*j*) C. S. Yi and R. Gao, *Organometallics*, 2009, **28**, 6585–6592.
11 S. Ye and W. K. Leong, *J. Organomet. Chem.*, 2006, **691**, 1117–1120.
12 W.-L. Wong, K.-C. Cheung, P.-H. Chan, Z.-Y. Zhou, K.-H. Lee and K.-Y. Wong, *Chem. Commun.*, 2007, 2175–2177.
13 A small amount of acetophenone (<5%) was also produced as a side-product in all cases of the catalysis investigated.
14 (*a*) J. M. Lynam, *Chem.–Eur. J.*, 2010, **16**, 8238–8247; (*b*) S. Rigaut, D. Touchard and P. H. Dixneuf, *Coord. Chem. Rev.*, 2004, **248**, 1585–1601; (*c*) H. Katayama and F. Ozawa, *Coord. Chem. Rev.*, 2004, **248**, 1703–1715.
15 B. Çetinkaya, N. Gürbüz, T. Seçkin and I. Özdemir, *J. Mol. Catal. A: Chem.*, 2002, **184**, 31–38.