Available online at www.sciencedirect.com
ScienceDirect
Mendeleev Commun., 2024, **34**, 57–60

Mendeleev Communications

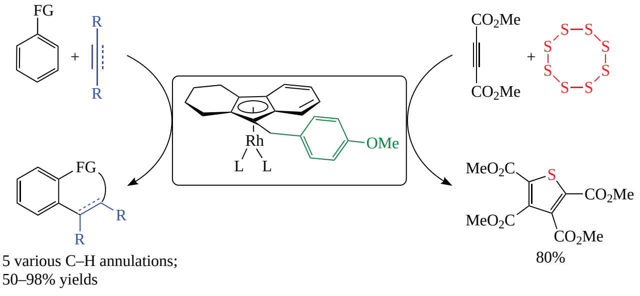
Tetrahydrofluorenyl rhodium complexes: positive impact of *p*-methoxybenzyl substituent on catalytic annulation reactions

Vladimir B. Kharitonov,[a] **Yulia V. Nelyubina,**[a] **Dmitry V. Muratov**[a] **and Dmitry A. Loginov***[a,b]

[a] *A. N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, 119334 Moscow, Russian Federation. Fax: +7 499 135 5085; e-mail: dloginov@ineos.ac.ru*
[b] *G. V. Plekhanov Russian University of Economics, 117997 Moscow, Russian Federation*

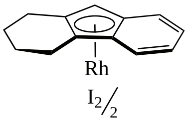
DOI: 10.1016/j.mencom.2024.01.017

Rhodium complex based on 9-(*p*-methoxybenzyl)-1,2,3,4-tetrahydrofluorenyl ligand was found to be an efficient catalyst for various C–H annulation reactions such as couplings of benzoic acids with alkynes, pivaloyl hydroxamate with alkenes, or the tandem reaction of *p*-anisaldehyde and *p*-toluidine with tolane. The catalyst demonstrated higher catalytic performance than the unsubstituted analog due to the stabilization of the rhodium–tetrahydrofluorenyl bond. Tetrahydrofluorenyl rhodium complexes also effectively catalyzed the synthesis of tetramethyl thiophene-2,3,4,5-tetracarboxylate from elemental sulfur and dimethyl acetylenedicarboxylate.

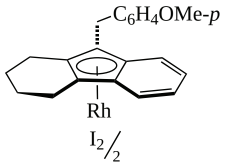


Keywords: alkynes, C–H annulation, indenyl ligand, rhodium complexes, homogeneous catalysis.

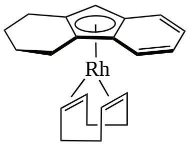
Transition metal-catalyzed C–H activation of aromatic compounds followed by annulation with alkenes or alkynes is an efficient atom- and step-economy construction of various heterocyclic compounds.[1–4] Usually, rhodium(III) complexes with cyclopentadienyl ligands demonstrate the highest catalytic performance when these strongly bound ligands act as supporting ones to stabilize the catalytic rhodium species.[5–8] At the same time, related indenyl ligands represent a promising framework for the design of future catalysts due to the possible indenyl effect.[9–12] However, the use of the indenyl complexes in catalysis is often limited by the low stability of real catalytic species, which is caused by the same indenyl effect. In particular, we earlier[13,14] found that rhodium and iridium complexes with the parent unsubstituted indenyl ligand $[(\eta^5\text{-indenyl})MI_2]_n$ (M = Rh, Ir) exhibited very low catalytic efficiency in C–H annulation, *e.g*., in coupling of benzoic acids with alkynes TON value was less than 10. It is well known that the introduction of substituents into a cyclic π-ligand can stabilize its bond with the metal atom. For example, Rovis's and Tanaka's groups earlier reported[15,16] functionalized indenyl complexes $[(\eta^5\text{-heptamethylindenyl})RhCl_2]_2$ and $[(\eta^5\text{-1-EtO}_2\text{C-2-Me-3-Bn-indenyl})RhCl_2]_2$, which proved to be efficient catalysts for the annulation of benzamides with 3,3-disubstituted cyclopropenes or acetanilides with internal alkynes, respectively. Recently, we proposed to use readily available 1,2,3,4-tetrahydrofluorene as a precursor for the preparation of stabilized indenyl complexes.[17] Complex $[(\eta^5\text{-tetrahydrofluorenyl})RhI_2]_2$ **1** showed moderate to high catalytic activity in the C–H annulations of diverse aromatic compounds (such as benzoic acid, benzamide, acetanilide, *etc*.) with alkynes. Moreover, Shi with co-workers successfully used 1,2,3,4-tetrahydrofluorene to design a catalyst for the rare earth-catalyzed copolymerization of butadiene with styrene.[18] Herein, we report a further improvement of the catalytic efficiency of rhodium complexes that was achieved by introducing a *p*-methoxybenzyl (PMB) substituent into the tetrahydrofluorenyl ligand. Complexes **1–4** were tested as catalysts.



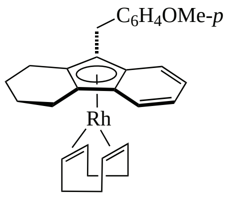
1



2



3

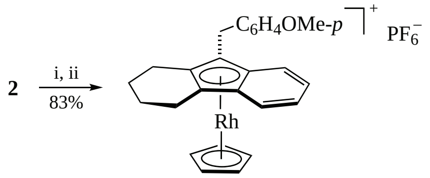


4

Complex **2** with PMB substituent was easily prepared from fluorene using our previous procedure.[19] Unfortunately, we were unable to grow crystals of **2** suitable for X-ray diffraction study. Therefore, in the present work, to indirectly confirm its structure, cyclopentadienyl hexafluorophosphate derivative **5** was synthesized by the reaction of **2** with CpTl (Scheme 1), and then it was structurally characterized (Figure 1).[†] In the structure of

---

[†] *Crystal data for* **5**. $C_{26}H_{26}F_6OPRh$ (M = 602.35), monoclinic, space group $P2_1/n$, at 293 K, a = 8.8150(18), b = 13.986(3) and c = 19.100(4) Å, β = 90.11°, V = 2354.8(8) Å^3, Z = 4, d_{calc} = 1.699 g cm^{-3}, μ(MoKα) = 9.96 cm^{-1}, $F(000)$ = 1216. A total of 14281 reflections were collected (3802 independent reflections, R_{int} = 0.0852) and used in the refinement, which converged to wR_2 = 0.1891 and GOOF = 1.058



5

Scheme 1 *Reagents and conditions*: i, CpTl, MeCN, room temperature, 24 h; ii, KPF_6, H_2O.

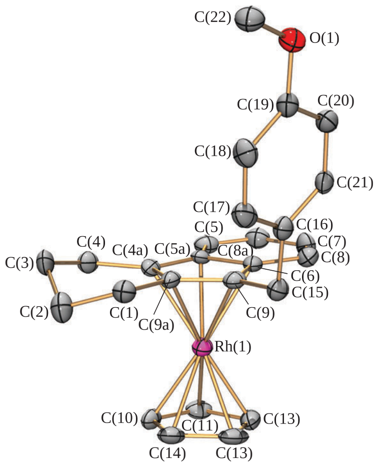


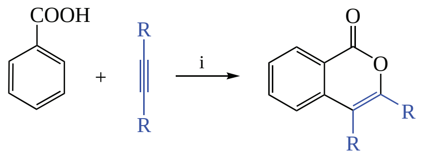
Figure 1 Molecular structure of cation of salt **5** in the representation of atoms as 50% probability ellipsoids; hydrogen atoms are omitted. Selected bond lengths (Å): Rh(1)−C(4a) 2.169(9), Rh(1)−C(5a) 2.219(8), Rh(1)−C(8a) 2.224(9), Rh(1)−C(9a) 2.167(8), Rh(1)−C(9) 2.164(9), Rh(1)−C(10) 2.181(10), Rh(1)−C(11) 2.183(10), Rh(1)−C(12) 2.178(11), Rh(1)−C(13) 2.176(11), Rh(1)−C(14) 2.161(10), C(4a)−C(5a) 1.415(14), C(4a)−C(9a) 1.435(13), C(5a)−C(8a) 1.445(13), C(9)−C(9a) 1.408(14), C(9)−C(8a) 1.446(15), C(10)−C(11) 1.400(16), C(11)−C(12) 1.440(16), C(12)−C(13) 1.399(19), C(13)−C(14) 1.396(18), C(10)−C(14) 1.417(16).

cation of molecule **5**, the *p*-methoxyphenyl substituent of the PMB moiety is bent almost perpendicularly in the direction opposite to the rhodium atom, and therefore does not induce a significant additional steric load. Indeed, the Rh···tetrahydrofluorenyl distance in **5** (1.819 Å) is very close to that (1.822 Å) in the unsubstituted tetrahydrofluorenyl derivative [(η^5-1,2,3,4-tetrahydrofluorenyl)RhCp]TlI_4.[17]

To estimate the stabilization of the Rh−indenyl bonding, we performed energy decomposition analysis (EDA)[23,24] for cation of salt **5** and the related complexes [(η^5-1,2,3,4-tetrahydrofluorenyl)RhCp]$^+$ and [(η^5-indenyl)RhCp]$^+$ at the GGABP-D3/TZP level using the COSMO solvation model with methanol as a solvent (Table 1). This method has already proven its usefulness for the analysis of the nature of the metal−indenyl bonding in sandwich compounds.[25,26] We found that the introduction of the PMB substituent into the tetrahydrofluorenyl ligand leads to an increase in the dissociation energy (D_e) by *ca*. 7 kcal mol^{-1}. Notably, the same magnitude of strengthening of the Rh−indenyl bond is observed for the tetrahydrofluorenyl ligand compared with the unsubstituted indenyl. In both cases, the stabilization is caused mainly by an increase of the attractive orbital interactions (ΔE_{orb}).

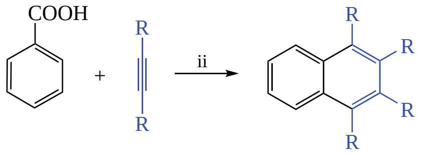
We tested the PMB-substituted complex **2** as a catalyst at loadings of 1–1.5 mol% in several reactions of C–H annulation and compared its catalytic efficiency with that of complex **1** (Schemes 2 and 3). In general, complex **2** proved to be more active giving the target products in higher yields compared to **1**, which is in accordance with the additional stabilization of the Rh−tetrahydrofluorenyl bond by the PMB substituent. It should be noted that complex **2** demonstrates excellent selectivity in the

(*a*) Annulation of benzoic acid with alkynes under mild conditions



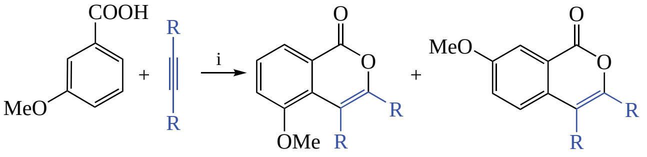
R = Ph, 80% (*vs*. 60% for **1**)
R = Et, 97% (*vs*. 91% for **1**)

(*b*) Annulation of benzoic acid with alkynes under harsh conditions



R = Ph, 83% (*vs*. 57% for **1**)
R = Et, 98%
(*vs*. 65% + 31% of isocoumarin for **1**)

(*c*) Annulation of 3-methoxybenzoic acid
with alkynes under mild conditions



R = Ph, 97%, *rr* 2.2 : 1 (*vs*. 87%, *rr* 1.75 : 1 for **1**)
R = Et, 98%, *rr* 2.0 : 1 (*vs*. 96%, *rr* 1.70 : 1 for **1**)

Scheme 2 *Reagents and conditions*: i, **2** (1.0 mol%), AgOAc (1.5 equiv.), MeOH, 80 °C, 10 h; ii, **2** (1.0 mol%), $Cu(OAc)_2$ (2 equiv.), *o*-xylene, 160 °C, 10 h.

Table 1 Results of EDA for cations [(L)RhCp]$^+$ using [CpRh]$^{2+}$ and [L]$^-$ as interacting fragments at the GGABP-D3/TZP level.

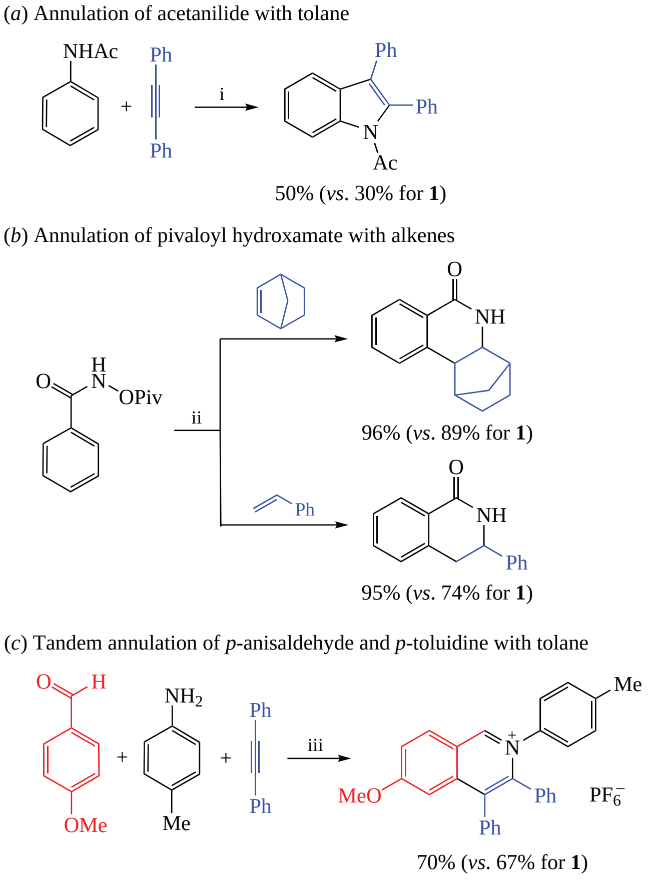
Ligand L	Energies/kcal mol^{-1}					
	ΔE_{int}	ΔE_{Pauli}	ΔE^a_{elstat}	ΔE^a_{orb}	ΔE_{prep}	D_e
Indenyl	–393.77	158.15	–283.13 (56.5%)	–217.90 (43.5%)	3.99	389.78
Tetrahydrofluorenyl	–402.27	165.99	–280.24 (54.2%)	–236.62 (45.8%)	5.65	396.62
9-PMB-tetrahydrofluorenyl^b	–409.94	173.45	–274.22 (52.2%)	–251.52 (47.8%)	6.40	403.54

^{a}The values in parentheses give the percentage contribution to the total attractive interactions. ^{b}As in compound **5**.

---

for the independent reflections [R_1 = 0.0686 was calculated for 3124 reflections with $I > 2\sigma(I)$]. Crystals were grown by slow interdiffusion of a two-phase system containing ether and a solution of compound in acetone. Crystallographic data were collected at the K4.4 station of the Kurchatov Center for Synchrotron Radiation and Nanotechnology in Moscow (Russia) at a wavelength of 0.7527 Å. Using Olex2,[20] the structure was solved with the ShelXT[21] structure solution program using Intrinsic Phasing and refined with the XL[22] refinement package using Least-Squares minimization against F^2 in anisotropic approximation for non-hydrogen atoms. The positions of hydrogen atoms were calculated, and they were refined in the isotropic approximation in the riding model.

CCDC 2299178 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* http://www.ccdc.cam.ac.uk.


(*a*) Annulation of acetanilide with tolane

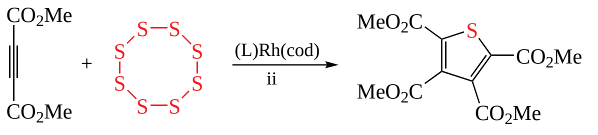
(*b*) Annulation of pivaloyl hydroxamate with alkenes

(*c*) Tandem annulation of *p*-anisaldehyde and *p*-toluidine with tolane

Scheme 3 *Reagents and conditions*: i, **2** (1.0 mol%), $Cu(OAc)_2$ (10 mol%), $AgSbF_6$ (10 mol%), O_2 (air), acetone, room temperature, 50 h; ii, **2** (1.5 mol%), CsOAc (25 mol%), CH_2Cl_2, room temperature, 1 h; iii, **2** (1.0 mol%), AgOAc (1 equiv.), MeOH, 80 °C, 16 h.

annulation of benzoic acid with hex-3-yne under harsh conditions (*o*-xylene, 160 °C)[27] affording 1,2,3,4-tetraethylnaphthalene as the only product, whereas from the reaction catalyzed by complex **1**, 3,4-diethylisocoumarin was also isolated (see Scheme 2, part *b*). At the same time, the presence of the PMB substituent at position 9 does not affect the regioisomeric ratio (*rr*) of the annulation products from 3-methoxybenzoic acid and alkynes, which suggests that this substituent has a minor effect on steric hindrance at the rhodium atom. Under mild conditions (MeOH, 80 °C),[7] both catalysts **1** and **2** lead predominantly to less sterically favorable 5-MeO-substituted isocoumarins (see Scheme 2, part *c*; for more examples of the use of complex **2** in the synthesis of isocoumarins, see also Online Supplementary Materials). The same regioselectivity was earlier observed for reactions catalyzed by cyclopentadienyl rhodium complexes.[28] Moreover, we found that complex **2** also proved to be the best catalyst among indenyl rhodium complexes for the annulation of acetanilide with tolane[29] and pivaloyl hydroxamate with alkenes,[30,31] as well as for the tandem annulation of *p*-anisaldehyde and *p*-toluidine with tolane[7,32,33] (see Scheme 3).

In addition to the C–H activation reactions in which the rhodium(III) complexes were used, we found that tetrahydrofluorenyl complexes of rhodium(I) **3** and **4** could effectively catalyze the activation of elemental sulfur in the reaction between S_8 and two equivalents of dimethyl acetylenedicarboxylate affording tetramethyl thiophene-2,3,4,5-tetracarboxylate (Scheme 4). Although this reaction has been well studied,[34,35] in previous works the best yield of the product was only 35%,[36] which was achieved for the cyclopentadienyl complex CpRh(cod). Using indenyl and tetrahydrofluorenyl complexes as catalysts, in this work we were able to more than double the yield. Notably, the highest yield (80%) was achieved in the case of PMB-substituted catalyst **4**.



Catalyst	Yield (%)
(Cp)Rh(cod)	35
(Indenyl)Rh(cod)	70
3	76
4	80

Scheme 4 *Reagents and conditions*: i, $MeO_2CC{\equiv}CCO_2Me$ (0.2 mmol), S_8 (0.02 mmol), catalyst (1 mol% or 0.7 mol% for L = Cp), *o*-xylene (1 ml), 150 °C, 8 h (or 130 °C, 16 h for L = Cp, see ref. 36). Isolated yields are given.

In summary, we have demonstrated the positive effect of PMB substituent in tetrahydrofluorenyl rhodium complexes on their catalytic efficiency in different annulation reactions. This effect is ensured by the stabilization of the catalytic particles due to the strengthening of the rhodium–tetrahydrofluorenyl bond. An additional advantage of the proposed catalysts is a simple one-step procedure of incorporation of the PMB substituent into the tetrahydrofluorenyl framework by alkylation with *p*-anisaldehyde.[19]

This work was supported by the Russian Science Foundation (grant no. 19-73-20212). D.A.L. is also thankful to the Plekhanov Russian University of Economics for providing access to computation resources for DFT calculations. The NMR studies were performed using the equipment of Center for Molecular Composition Studies of INEOS RAS with the financial support from the Ministry of Science and Higher Education of the Russian Federation (contract/agreement no. 075-03-2023-642).

Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2024.01.017.

References

1 T. Satoh and M. Miura, *Chem. – Eur. J.*, 2010, **16**, 11212.
2 G. Song and X. Li, *Acc. Chem. Res.*, 2015, **48**, 1007.
3 V. B. Kharitonov, D. V. Muratov and D. A. Loginov, *Coord. Chem. Rev.*, 2022, **471**, 214744.
4 B. A. Shainyan, *Russ. Chem. Rev.*, 2022, **91**, RCR5052.
5 G. Song, F. Wang and X. Li, *Chem. Soc. Rev.*, 2012, **41**, 3651.
6 A. V. Kolos and D. S. Perekalin, *Mendeleev Commun.*, 2021, **31**, 1.
7 V. B. Kharitonov, D. V. Muratov, Y. V. Nelyubina, I. A. Shutkov, A. A. Nazarov and D. A. Loginov, *J. Org. Chem.*, 2023, **88**, 2869.
8 D. V. Vorobyeva, A. S. Bubnova, A. G. Buyanovskaya and S. N. Osipov, *Mendeleev Commun.*, 2023, **33**, 34.
9 M. J. Calhorda, C. C. Romão and L. F. Veiros, *Chem. – Eur. J.*, 2002, **8**, 868.
10 V. B. Kharitonov, D. V. Muratov and D. A. Loginov, *Coord. Chem. Rev.*, 2019, **399**, 213027.
11 S. Ouchi, T. Inoue, J. Nogami, Y. Nagashima and K. Tanaka, *Nat. Synth.*, 2023, **2**, 535.
12 L. Atkin and D. L. Priebbenow, *Angew. Chem., Int. Ed.*, 2023, **62**, e202302175.
13 V. B. Kharitonov, M. Makarova, M. A. Arsenov, Y. V. Nelyubina, O. Chusova, A. S. Peregudov, S. S. Zlotskii, D. Chusov and D. A. Loginov, *Organometallics*, 2018, **37**, 2553.
14 A. A. Chamkin, A. M. Finogenova, Y. V. Nelyubina, J. Laskova, A. R. Kudinov and D. A. Loginov, *Mendeleev Commun.*, 2016, **26**, 491.
15 N. Semakul, K. E. Jackson, R. S. Paton and T. Rovis, *Chem. Sci.*, 2017, **8**, 1015.
16 J. Terasawa, Y. Shibata, Y. Kimura and K. Tanaka, *Chem. – Asian J.*, 2018, **13**, 505.

17 V. B. Kharitonov, S. A. Runikhina, Y. V. Nelyubina, D. V. Muratov, D. Chusov and D. A. Loginov, *Chem. – Eur. J.*, 2021, **27**, 10903.
18 S. Xu, Y. Huo, X. Hu, F. Wang, L. Pan and X. Shi, *Inorg. Chem.*, 2023, **62**, 4980.
19 M. A. Losev, A. S. Kozlov, V. B. Kharitonov, O. I. Afanasyev, F. S. Kliuev, L. A. Bulygina, N. S. Khrushcheva, D. A. Loginov and D. Chusov, *Org. Biomol. Chem*., 2023, **21**, 8477.
20 O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard and H. Puschmann, *J. Appl. Crystallogr.*, 2009, **42**, 339.
21 G. M. Sheldrick, *Acta Crystallogr*., 2015, **A71**, 3.
22 G. M. Sheldrick, *Acta Crystallogr*., 2008, **A64**, 112.
23 G. Frenking, *J. Organomet. Chem.*, 2001, **635**, 9.
24 M. J. S. Phipps, T. Fox, C. S. Tautermann and C.-K. Skylaris, *Chem. Soc. Rev.*, 2015, **44**, 3177.
25 D. A. Loginov, A. A. Chamkin, V. B. Kharitonov, E. R. Sovdagarova, Y. V. Nelyubina and A. R. Kudinov, *ChemistrySelect*, 2017, **2**, 3549.
26 V. B. Kharitonov, Y. V. Nelyubina, I. D. Kosenko and D. A. Loginov, *J. Organomet. Chem.*, 2019, **880**, 312.
27 K. Ueura, T. Satoh and M. Miura, *J. Org. Chem.*, 2007, **72**, 5362.
28 V. B. Kharitonov, D. V. Muratov, Y. V. Nelyubina and D. A. Loginov, *Catalysts*, 2023, **13**, 389.
29 Y. Hoshino, Y. Shibata and K. Tanaka, *Adv. Synth. Catal.*, 2014, **356**, 1577.
30 S. Rakshit, C. Grohmann, T. Besset and F. Glorius, *J. Am. Chem. Soc.*, 2011, **133**, 2350.
31 N. Guimond, S. I. Gorelsky and K. Fagnou, *J. Am. Chem. Soc.*, 2011, **133**, 6449.
32 J. Jayakumar, K. Parthasarathy and C.-H. Cheng, *Angew. Chem., Int. Ed.*, 2012, **51**, 197.
33 K. Parthasarathy, N. Senthilkumar, J. Jayakumar and C.-H. Cheng, *Org. Lett.*, 2012, **14**, 3478.
34 M. Arisawa, K. Sawahata, T. Ichikawa and M. Yamaguchi, *Organometallics*, 2018, **37**, 3174.
35 M. Arisawa and M. Yamaguchi, *Synlett*, 2019, **30**, 1621.
36 M. Kajitani, T. Suetsugu, R. Wakabayashi, A. Igarashi, T. Akiyama and A. Sugimori, *J. Organomet. Chem.*, 1985, **293**, C15.

Received: 11th October 2023; Com. 23/7267