CCS CHINESE CHEMICAL SOCIETY

SIOC 1950

ROYAL SOCIETY OF CHEMISTRY

RESEARCH ARTICLE

Check for updates

Acid-mediated decarboxylative C−H coupling between arenes and *O*-allyl carbamates†

Camilla Loro, [a,b] Julie Oble, [b] Francesca Foschi, [a] Marta Papis, [a] Egle M. Beccalli, [c] Sabrina Giofrè, [c] Giovanni Poli *[b] and Gianluigi Broggini *[a]

Treatment of *O*-allyl *N*-tosyl carbamates with aromatic compounds in the presence of $Cu(OTf)_2$ or TMSOTf as promoters affords *N*-substituted 1-arylpropan-2-amines, 1,2-diarylpropanes, 1,1-diarylpropanes, or indanes, depending on the nature of the promoter and of the aryl substrates. A full mechanistic rational allowing appreciation of the outcome of these novel C−H based cascades is proposed. An initial acid promoted decarboxylative/deamidative Friedel−Crafts allylation takes place. After protonation of the allylated arene, evolution of the resulting cation may follow different paths depending on the nature of the arene partner and of the allyl moiety in the carbamate.

Introduction

In the last century, carbocation-mediated or -catalysed reactions have revolutionised the history of organic chemistry, giving rise to a set of fundamental reactions such as C–C bond formations, eliminations, and rearrangements.[1] In particular, the Friedel–Crafts (FC) alkylation is one of the most powerful organic reactions that allows the selective C–H functionalization of aromatics.[2] Although the FC alkylation has long been studied in many variations, its implementation in cascade reactivities that allow the multiple functionalizations of unsaturated substrates represents an extraordinary way to discover still unexplored reactivity patterns.[3]

In the frame of our long-term study dedicated to carbamates as precursors for metal-catalysed cyclisations,[4] we investigated in particular the behaviour of *O*-allyl *N*-tosyl carbamates. These compounds have been shown to undergo *exo*-[5] or *endo-trig*[6] cyclisations involving further functionalisation of the carbon double bond. Moreover, allyl carbamates can also allow decarboxylative *O* → *N* allylic rearrangement affording selectively *anti*-Markovnikov hydroamination products.[7] In this work, we show that *O*-allyl carbamates behave as C3 1,2-, 1,1-, and 1,3-dication equivalents, allowing the generation of 1-aryl-

propan-2-amines, 1,2- and 1,1-diarylpropanes, as well as indane structures, in the presence of $Cu(OTf)_2$ or TMSOTf as acid-promoters (Scheme 1).

Results and discussion

We started our study reacting carbamate **1a** in mesitylene, as aromatic reaction partner and solvent, in the presence of copper(II) triflate as the promoter (Table 1, entry 1). After 6 hours at 100 °C, the reaction provided a mixture of the arylated *N*-tosylamide **2** (36% isolated), together with a big amount of $TsNH_2$ (**4**) arising from the degradation of **1a**. Unchanged starting material was found working at lower temperature, and using a catalytic amount of $Cu(OTf)_2$ (entries 2 and 3). Although using an excess of copper salt at 130 °C led to an increased yield of **2**, the formation of **4** could not be
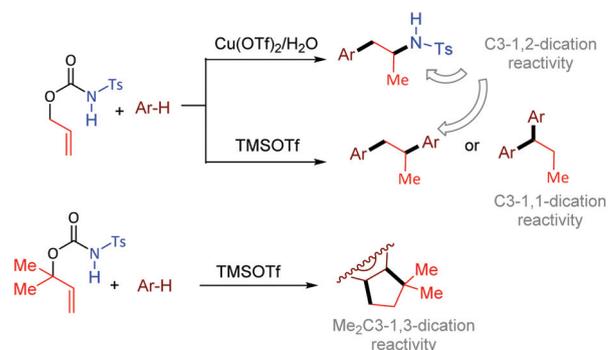
Scheme 1 Different reactivities in the acid promoted coupling between arenes and *O*-allyl *N*-tosyl carbamates observed in the present study (*bold bonds refer to forming bonds*).
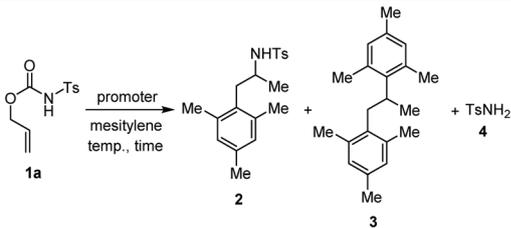
[a]*Dipartimento di Scienza e Alta Tecnologia, Università degli Studi dell'Insubria, via Valleggio 9, 22100 Como, Italy. E-mail: gianluigi.broggini@uninsubria.it*
[b]*Sorbonne Université, Faculté des Sciences et Ingénierie, CNRS, Institut Parisien de Chimie Moléculaire, IPCM, 4 place Jussieu, 75005 Paris, France.*
E-mail: giovanni.poli@sorbonne-universite.fr
[c]*DISFARM, Sezione di Chimica Generale e Organica "A. Marchesini", Università degli Studi di Milano, via Venezian 21, 20133 Milano, Italy*
†Electronic supplementary information (ESI) available. See DOI: 10.1039/d2qo00114d

This journal is © the Partner Organisations 2022

Org. Chem. Front., 2022, **9**, 1711–1718 | **1711**

Table 1 Optimization of reaction conditions[a]

Entry	Promoter (equiv.)	Temp. (°C)	Time (h)	Product(s) (% yield)[b]
1	Cu(OTf)$_2$ (1.0)	100	6.0	**2** (36) + **4** (43)
2	Cu(OTf)$_2$ (1.0)	50	24	S.M.
3	Cu(OTf)$_2$ (0.1)	100	24	S.M.
4	Cu(OTf)$_2$ (4.0)	130	3.0	**2** (85) + **4** (11)
5	Cu(OTf)$_2$ (4.0)[c]	130	4.0	**2** (77) + **4** (22)
6	PTSA (4.0)	130[d]	1.5	**2** (59) + **4** (18)
7	H$_2$SO$_4$ (1.0)	130	4.0	**2** (25) + **4** (14)
8	AgOTf (4.0)	130	1.5	**2** (25) + **4** (31)
9	TfOH (0.05)	130	4.0	**2** (69) + **4** (26)
10	TfOH (0.05)[e]	130	4.0	**2** (58) + **4** (41)
11	TfOH (0.05)[f]	130	4.0	degr. products
12	BF$_3$·Et$_2$O (1.0)	100[d]	0.5	**2** (21) + **3** (63)
13	BF$_3$·Et$_2$O (4.0)	130[d]	1.5	**2** (15) + **3** (72)
14	TMSOTf (0.05)	130	3.0	**2** (23) + **4** (41)
15	TMSOTf (4.0)	130	3.0	**3** (89)
16	TMSOTf (4.0)[g]	80	4.0	**3** (79)

[a] Reaction conditions: **1a** (1.0 equiv.), mesitylene (0.25 M), oil bath as heat source. [b] Isolated yields. [c] Chlorobenzene/H$_2$O as solvent (96/4 v/v) (0.4 M) with mesitylene (5.0 equiv.). [d] MW irradiation at 300 W. [e] Chlorobenzene as the solvent (0.25 M) with mesitylene (5.0 equiv.). [f] DMF as the solvent (0.25 M) with mesitylene (5.0 equiv.). [g] DCE (0.25 M) with mesitylene (5.0 equiv.).

avoided (entry 4). Carrying out the reaction in chlorobenzene in the presence of mesitylene (5.0 equiv.) and H$_2$O (96/4 v/v) allowed to obtain **2** and **4** in 77% and 22% yields, respectively (entry 5). Although this protocol does not represent an improvement in terms of yields, it shows that it is possible to work in the presence of a solvent other than the aromatic reaction partner itself.

Different promoters were then tested, using either conventional heating or microwave irradiation. However, p-toluenesulfonic acid, H$_2$SO$_4$ and silver(ι) triflate behaved analogously to Cu(OTf)$_2$ (Table 1, entries 6–8). Assuming that the above described reaction conditions involved the *in situ* generation of TfOH, we also tested a catalytic amount of this acid in different solvents (entries 9–11). Working in mesitylene or in chlorobenzene with 5.0 equivalents of mesitylene, the recovery of TsNH$_2$ was still high, whereas the use of DMF gave only intractable degradation products. The use of F$_3$B·OEt$_2$ disclosed a new reactivity involving the double arylation to the allyl moiety. Indeed, treatment of **1a** with a stoichiometric or an excess amount of F$_3$B·OEt$_2$ under microwave irradiation furnished a mixture of **2** and the 1,2-diarylpropane **3** (entries 12 and 13). Switch to TMSOTf as the acid promoter was then considered. While the use of a catalytic amount of this promoter afforded a mixture of **2** and **4** (entry 14), an excess amount

of it (4.0 equiv.) gladly brought about the selective formation of **3** in 89% yield (entry 15). A similar result was also obtained using DCE as solvent (entry 16).

Among the range of branched amines, *N*-substituted phenethylamine derivatives have been widely studied in recent years for their value in organic, bioorganic, and medicinal chemistry.[8] We thus set out to test the decarboxylative arylation/hydroamination described above with other aromatic hydrocarbons (Table 2).

Accordingly, reacting allyl carbamate **1a** in *p*-xylene under the conditions of Table 1, entry 5 [Cu(OTf)$_2$ (4 equiv.), chlorobenzene[9]/H$_2$O (96/4 v/v), 130 °C, 4.0 h] afforded the corresponding arylated 2-tosylaminopropane **5** as the sole product in good yield (Table 2, entry 1). The reaction carried out in *o*-xylene, *m*-xylene, or toluene gave the corresponding arylation/hydroamination products as mixtures of two regioisomers **6a/6b**, **7a/7b**, and **8a/8b** (entries 2–4). The less electron-rich benzene also provided the expected arylation/hydroamination product **9**[10] in acceptable yield (entry 5). Finally, the heavily alkylated arenes durene and 1,3,5-triethylbenzene gave the

Table 2 Synthesis of the *N*-substituted phenethylamines[a]
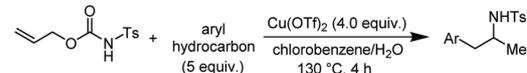
Entry	Aryl hydrocarbon	Product(s) (% yield)[b]
1[c]	*p*-Xylene	**5** (79%)
2	*o*-Xylene	**6a / 6b** (76%, 1/2)
3	*m*-Xylene	**7a / 7b** (72%, 1/1)
4	Toluene	**8a / 8b** (29%, 1/2)
5	Benzene	**9** (73%)
6	1,2,4,5-Tetramethylbenzene	**10** (78%)
7	1,3,5-Triethylbenzene	**11** (74%)

[a] Reaction conditions: **1a** (1.0 equiv.), Cu(OTf)$_2$ (4.0 equiv.), aryl hydrocarbon (5.0 equiv.), chlorobenzene/H$_2$O as solvent (96/4 v/v) (0.4 M), 130 °C, 4 h. [b] Isolated yields. Isomeric ratios calculated from the ^{1}H-NMR of the crude reaction mixture. [c] Scale up: performing the reaction with 5 mmol of **1a** at 130 °C, after 6 h **5** was obtained in 71% yield.

1712 | *Org. Chem. Front.*, 2022, **9**, 1711–1718

This journal is © the Partner Organisations 2022

corresponding cascade products **10** and **11** in good yields (entries 6 and 7).

We propose for the above double coupling reactions the following mechanism, shown in the case of carbamate **1a** (Scheme 2). First, we assume that triflic acid is formed *in situ* from Cu(OTf)$_2$ (or TMSOTf) and water.[11] Following protonation at the carbonyl oxygen atom of the carbamate function generates the activated *O*-allyl carbamate **I**, which undergoes a decarboxylative/deamidative FC alkylation by attack of arene to give intermediate **III** passing through an allyl carbenium ion **II**. Subsequent Markovnikov protonation of **III** generates the allyl carbenium ion **IV**. At this point, the nature of the additive directs the reaction path. In the presence of copper triflate, the extruded *N*-tosylamide can coordinate the metal, generating the amido copper-complex **V**, which selectively attacks the carbenium ion **IV**, affording the hydroamination product **2**.[12] Alternatively, when TMSOTf is used, intermediate **IV** undergoes a second FC allylation, providing the 1,2-diarylpropane **3**. Finally, in the presence of excess triflic acid product **2** suffers a deamidative substitution by mesitylene *via* an incipient or discrete carbenium ion, to afford the diarylated product **3**.

Corollary experiments using the *O*-allyl *N*-4-chlorophenyl carbamate **1b** in place of **1a** were carried out next (Scheme 3). Running the reaction in mesitylene/H$_2$O (98/2 v/v) in the presence of Cu(OTf)$_2$ as the promoter gave the diarylated product **3**, and not the corresponding aniline derivative. However, carrying out the same reaction in the presence of exogenous

H$_2$NTs (2.0 equiv.) afforded a mixture of the arylated/hydroaminated derivative **2** and the diarylated derivative **3**. These results corroborate the above proposed mechanism and show that tosylamine is a competent nitrogen nucleophile to trap the carbenium ion **IV** when Cu(OTf)$_2$ is used as the promoter.

The scope of the reaction was evaluated next, keeping the promoting system Cu(OTf)$_2$/H$_2$O in chlorobenzene (Table 3). On the one hand, reacting *O*-allyl *N*-2-nosylcarbamate **1c** with 5 equiv. of mesitylene (entry 1), and carbamate **1a** with mesityl bromide (entry 2), 4-methylanisole (entry 3), 4-bromoanisole (entry 4) gave the corresponding hydroaminated products **12–15** in fair to good yields. On the other hand, strongly activated arenes such as 1,3,5-trimethoxybenzene gave the diarylated product **16** as the only product (entry 5).

To have a better knowledge of the behaviour of this C–H cascade as a function of the adopted reaction protocol and the nature of the engaged reaction partners, other tests were undertaken. Accordingly, the C–H coupling between variously substituted *N*-tosyl carbamates in the presence of the Cu (OTf)$_2$/H$_2$O system and 5.0 equivalents of arene was next tested (Scheme 4). In the event, each isomeric carbamate **1d–f** converged toward the same corresponding arylation/hydroamination product, namely **17** when reacted with mesitylene and **18** when reacted with *p*-xylene.

Such a reactivity suggests the convergence of **1d**, **1e** and **1f** toward the common allylic carbenium ion **VI**, which, after the
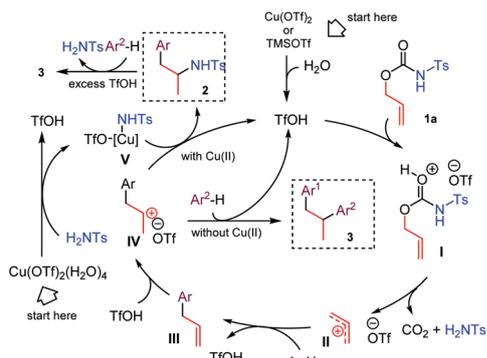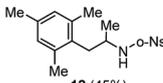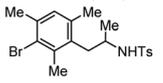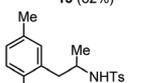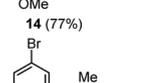

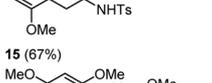**Scheme 2** Proposed mechanisms for the acid-mediated decarboxylative C–H coupling between arenes and *O*-allyl carbamates.
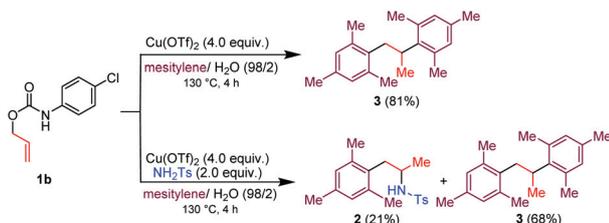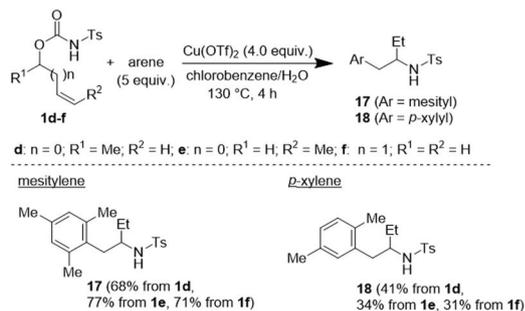

Scheme 3 Cu(OTf)$_2$/H$_2$O mediated decarboxylative C–H couplings between mesitylene and *O*-allyl *N*-4-chlorophenyl carbamate. Reaction condition involves the use of 100 μL of H$_2$O for 1 mmol of **1b**.

**Table 3** Other C–H couplings with heterosubstituted arenes[a]

Entry	Arene	PG	Product(s) (% yield)[b]
1[c]	Mesitylene	*o*-Ns	**12** (45%)
2	Mesitylbromide	Ts	**13** (82%)
3	4-Methylanisole	Ts	**14** (77%)
4	4-Bromoanisole	Ts	**15** (67%)
5	1,3,5-Trimethoxybenzene	Ts	**16** (61%)

[a] Reaction conditions: *N*-protected *O*-allyl carbamate (1.0 equiv.), Cu (OTf)$_2$ (4.0 equiv.), arene (5.0 equiv.), chlorobenzene/H$_2$O as solvent (96/4 v/v) (0.4 M), 130 °C, 4 h. [b] Isolated yields. [c] The reaction was carried out in mesitylene as solvent (0.25 M).

This journal is © the Partner Organisations 2022

Org. Chem. Front., 2022, **9**, 1711–1718 | **1713**

Scheme 4 Reaction with Cu(OTf)$_2$ with substituents on the allylic chain of the N-tosyl carbamates.
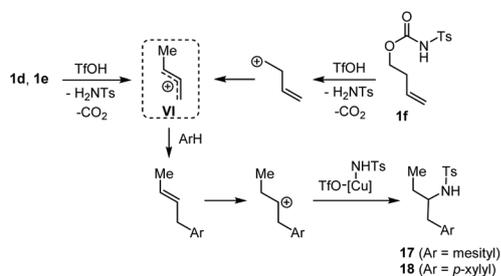
Scheme 5 Proposed mechanism for the Cu(OTf)$_2$ promoted transformation of **1d–f** into **17** and **18**.

FC reaction, undergoes a regioselective Cu-promoted hydroamination (Scheme 5).

The coupling of N-tosyl carbamates **1a**, and **1d–e** was also tested using TMSOTf as acid promoter in DCE at 80 °C (Table 4). In this case, reaction of **1a** with p-xylene gave an inseparable mixture made of the 1,2-diarylated product **19**, the 1,1-diarylated product **20**, and indane **21** (entry 1). Carbamates **1d** and **1e** converged again toward a mixture of the 1,1-diarylated product **22** and the indane **23** when reacted with p-xylene (entry 2), and toward a mixture of the 1,2-diarylated product **24** and 1,3-diarylated product **25** when reacted with mesitylene (entry 3).

The reactivity observed with the above experiments deserves further remarks. First, the formation of **19**, **20**, and **21** (Table 4, entry 1) can be rationalized as follows (Scheme 6, top part). After the first FC allylation of p-xylene, Markovnikov protonation and interception of the resulting carbenium ion **VII** by a second molecule of p-xylene generates **19**. However, p-xylene – less nucleophilic than mesitylene – allows a competitive **VII**-to-**VIII** 1,2-hydride shift that takes place before the second FC reaction, generating **20**. At this point, the benzylic carbocation **VIII** and the styrene **IX** could react together through a formal [3 + 2] cycloaddition giving the Wheland intermediate **X** which can evolve into **21**.[13]

The outcome of entry 3 in Table 4 needs further observations, too. Indeed, in this case, the protonation after the first

**Table 4** TMSOTf mediated C−H couplings involving differently substituted unsaturated carbamate derivatives[a]

Entry[d]	1	Arene	Product(s) (% yield)[b]
1[c]	**1a**	p-Xylene	**19 + 20** (61%)[c] **21** (35%)[d]
2	**1d, 1e**	p-Xylene	**22** from **1d**: 68% from **1e**: 73% **23**[d] from **1d**: 24% from **1e**: 21%
3	**1d, 1e**	Mesitylene	**24** from **1d**: 27% from **1e**: 32% **25** from **1d**: 69% from **1e**: 65%

[a] Reaction conditions: **1a** (1.0 equiv.), TMSOTf (4.0 equiv.), arene (5.0 equiv.), DCE (0.4 M), 80 °C, 4 h. [b] Isolated yields. Isomeric ratios calculated from the ^{1}H-NMR of the crude reaction mixture. [c] **19** + **20** isomeric ratio: 1/1. [d] The relative configuration of indane structures **21** and **23** was determined by NOESY experiment.

1714 | *Org. Chem. Front.*, 2022, **9**, 1711–1718

This journal is © the Partner Organisations 2022
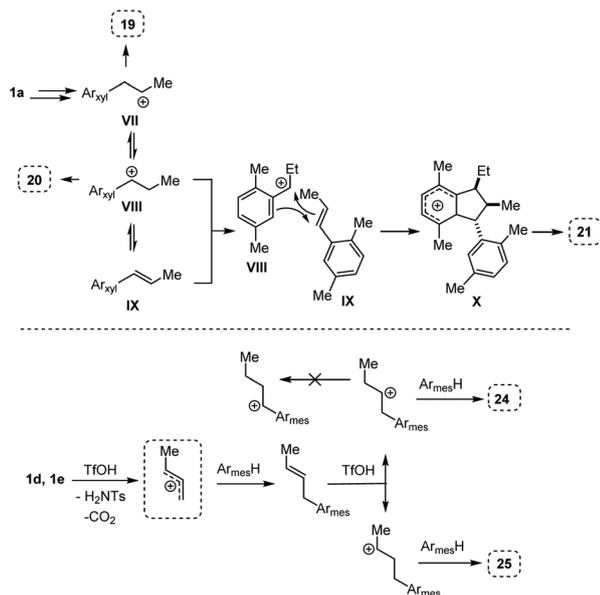
Scheme 6 Proposed mechanisms associated to the reactions of Table 5. Top part: entry 1, from **1a** to **19**, **20**, and **21**. Bottom part: entry 3, from **1d** or **1e** to **24** and **25**.

Table 5 Reaction with TMSOTf with α,α-dimethyl substituted *O*-allyl *N*-tosyl carbamates[a]

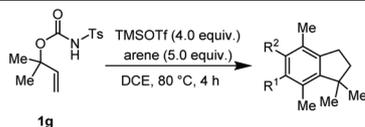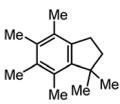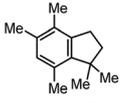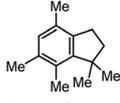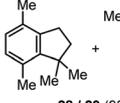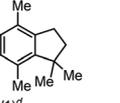| Entry	Arene	Product(s) (% yield)[b]
1	Durene	**26** (87%)
2[c]	Mesitylene	**27a / 27b** (89%, 1/1)[c]
3[d]	*p*-Xylene	**28 / 29** (93%, 1/1)[d]

[a] Reaction conditions: **1a** (1.0 equiv.), TMSOTf (4.0 equiv.), arene (5.0 equiv.), DCE (0.4 M), 80 °C, 4 h. [b] Isolated yields. Isomeric ratios calculated from the ^{1}H-NMR of the crude reaction mixture. [c] 1 : 1 isomeric ratio. [d] **28** + **29** in 1 : 1 ratio.

FC reaction is non-regioselective, and the very nucleophilic mesitylene intercepts the two resulting carbenium ions to give a mixture of **24** and **25**. In this case, the very reactive arene does not let the time for a homobenzylic-to-benzylic cation 1,2-hydride shift (Scheme 6, bottom part).
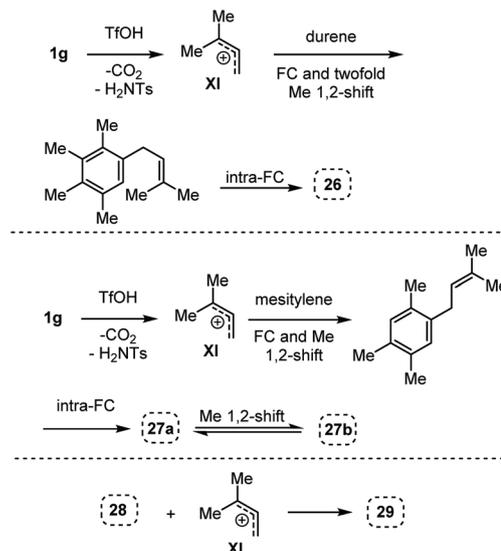
Scheme 7 Proposed mechanisms for the generation of the indane structures **26**, **27a** and **27b** and of hydrindacene **29** from carbamate **1g**.

The α,α-dimethyl substituted *O*-allyl *N*-tosyl carbamate **1g** was investigated next (Table 5). Thus, treatment of this carbamate with durene under the usual TMSOTf conditions gave indane **26** in 87% yield (entry 1). Analogous treatment with mesitylene afforded an inseparable mixture of the two isomeric indanes **27a** and **27b** in 89% yield (entry 2), while reaction with *p*-xylene gave an inseparable 1 : 1 mixture of the indane **28** and the hydrindacene **29** in 93% yield (entry 3).

Here, in contrast to the previous cases, a one-to-one coupling between the carbamate and the arene takes place, generating indane structures. This is likely due to the fact that after the first FC allylation on the less substituted allyl terminus **XI**,[14] the aromatic ring is favourably biased to undergo a second, intramolecular, FC reaction. It should be noted that in the cases of mesitylene and durene, 1,2-methyl migrations on the aryl moiety[15] take place – before or after the first FC reaction – opening the way to the final intramolecular FC reaction (Scheme 7). However, a second carbocation species could attack the highly reactive indane **28** providing the hydrindacene **29**.[16]

Conclusions

In summary, this work shows for the first time that *O*-allyl carbamates are ideal C3 dication equivalents. Acidic conditions expected to generate *in situ* TfOH enable decarboxylative FC/hydromidation sequences or twofold FC alkylations, most of which proceed in synthetically useful yields. According to the nature of the arene partner and of the allyl moiety in the carbamate, the mechanisms can take different paths, all of them mechanistically justified. These results offer the chemist a rich palette of synthetic opportunities, further enriching the

This journal is © the Partner Organisations 2022

Org. Chem. Front., 2022, **9**, 1711–1718 | **1715**

domains of cascade reactions in general, and FC, and hydroaminations in particular.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Notes and references

1 (*a*) G. A. Olah, in *100 Years of Carbocations and Their Significance in Chemistry*, ed. G. A. Olah and G. K. Surya Prakash, John Wiley and Sons, 2004, pp. 7–41; (*b*) R. R. Naredla and D. K. Klumpp, Contemporary carbocation chemistry: application in organic synthesis, *Chem. Rev.*, 2013, **113**, 6905–6948; (*c*) S. Y. Hong, D. Kim and S. Chang, Catalytic access to carbocation intermediates via nitrenoid transfer leading to allylic lactams, *Nat. Catal.*, 2021, **4**, 79–88; (*d*) G. A. Olah, in *Friedel–Crafts Chemistry*, Wiley, New York, 1973.

2 (*a*) M. Bandini and A. Umani-Ronchi, *Catalytic Asymmetric Friedel-Crafts Alkylations*, Wiley-VCH, Weinheim, 2009; (*b*) T. B. Poulsen and K. A. Jørgensen, Catalytic asymmetric Friedel-Crafts alkylation reactions-copper showed the way, *Chem. Rev.*, 2008, **108**, 2903–2915; (*c*) S.-L. You, Q. Cai and M. Zeng, Chiral Brønsted acid catalyzed Friedel-Crafts alkylation reactions, *Chem. Soc. Rev.*, 2009, **38**, 2190–2201; (*d*) M. Davoust, J. A. Kitching, M. J. Fleming and M. Lautens, Diastereoselective benzylic arylation of tetralins, *Chem. – Eur. J.*, 2010, **16**, 50–54; (*e*) D. Eom, S. Park, Y. Park, T. Ryu and P. H. Lee, Synthesis of indenes via Brønsted acid catalyzed cyclization of diaryl- and alkyl aryl-1,3-dienes, *Org. Lett.*, 2012, **14**, 5392–5395; (*f*) C. Zhai, D. Xing, C. Jing, J. Zhou, C. Wang, D. Wang and W. Hu, Facile synthesis of 3-aryloxindoles via Brønsted acid catalyzed Friedel-Crafts alkylation of electron-rich arenes with 3-diazooxindoles, *Org. Lett.*, 2014, **16**, 2934–2937; (*g*) M. M. Heravi, V. Zadsirjan, P. Saedi and T. Momeni, Applications of Friedel-Crafts reactions in total synthesis of natural products, *RSC Adv.*, 2018, **8**, 40061–40163; (*h*) K. Sakaguchi, S. Kubota, W. Akagi, N. Ikeda, M. Higashino, S. Ariyoshi, T. Shinada, Y. Ohfune and T. Nishimura, Acid-catalyzed chirality-transferring intramolecular Friedel-Crafts cyclization of α-hydroxy-α-alkenylsilanes, *Chem. Commun.*, 2019, **55**, 8635–8638; (*i*) C.-J. Wang, Q.-Q. Yang, M.-X. Wang, Y.-H. Shang, X.-Y. Tong, Y.-H. Deng and Z. Shao, Catalytic asymmetric

1,4-type Friedel-Crafts (hetero)arylations of 1-azadienes: the highly enantioselective syntheses of chiral hetero-triaryl-methanes, *Org. Chem. Front.*, 2020, **7**, 609–616; (*j*) H. Zheng, K. Dong, D. Wherritt, H. Arman and M. P. Doyle, Brønsted acid catalyzed Friedel-Crafts-type coupling and dedinitrogenation reactions of vinyldiazo compounds, *Angew. Chem., Int. Ed.*, 2020, **59**, 13613–13617, (*Angew. Chem.*, 2020, **132**, 13715–13719).

3 For a recent paper on C3 synthons, see: (*a*) M. Wienhold, J. J. Molloy, C. G. Daniliuc and R. Gilmour, Coumarins by direct annulation: β-borylacrylates as ambiphilic C$_3$-synthons, *Angew. Chem., Int. Ed.*, 2021, **60**, 685–689, (*Angew. Chem.*, 2021, **133**, 695–699); (*b*) S.-W. Xu, X.-W. Liu, X. Zuo, G. Zhou, Y. Gong, X.-L. Liu and Y. Zhou, Oxindole-chromones C3 synthons directed stereocontrolled construction of five contiguous stereocenters on spiro[tetrahydrocyclopenta[*b*]chromanone-oxindole]s, *Adv. Synth. Catal.*, 2019, **361**, 5328–5333; (*c*) J. Chen, P. Jia and Y. Huang, Divergent domino reactions of sulfur ylides: access to functionalized six- and seven-membered nitrogen-heterocycles, *Org. Lett.*, 2018, **20**, 6715–6718; (*d*) Z.-L. Jia, X.-T. An, Y.-H. Deng, H.-B. Wang, K. J. Gan, J. Zhang, X.-H. Zhao and C.-A. Fan, Palladium-catalyzed asymmetric (2 + 3) annulation of *p*-quinone methides with trimethylenemethanes: enantioselective synthesis of functionalized chiral spirocyclopentyl *p*-dieneones, *Org. Lett.*, 2020, **22**, 4171–4175; (*e*) J.-X. Zou, Y. Jiang, S. Lei, G.-F. Yin, X.-L. Hu, Q.-Y. Zhao and Z. Wang, Synthesis of α-arylthioacetones using TEMPO as the C$_3$ synthon via a reaction cascade of sequential oxidation, skeletal rearrangement and C-S bond formation, *Org. Biomol. Chem.*, 2019, **17**, 2341–2345; (*f*) F. Zhong, X. Han, Y. Wang and Y. Lu, Highly enantioselective [3 + 2] annulation of Morita-Baylis-Hillman adducts mediated by l-threonine-derived phosphines: synthesis of 3-spirocyclopentene-2-oxindoles having two contiguous quaternary centers, *Angew. Chem., Int. Ed.*, 2011, **50**, 7837–7841, (*Angew. Chem.*, 2011, **123**, 7983–7987); (*g*) X. Zhou, Z. Qi, S. Yu, L. Kong, Y. Li, W. F. Tian and X. Li, Synthesis of 2-substituted quinolines via rhodium(III)-catalyzed C-H activation of imidamides and coupling with cyclopropanols, *Adv. Synth. Catal.*, 2017, **359**, 1620–1625.

4 (*a*) S. Giofrè, C. Loro, L. Molteni, C. Castellano, A. Contini, D. Nava, G. Broggini and E. M. Beccalli, Copper(II)-catalyzed aminohalogenation of alkynyl carbamates, *Eur. J. Org. Chem.*, 2021, 1750–1757; (*b*) F. Foschi, C. Loro, R. Sala, J. Oble, L. Lo Presti, E. M. Beccalli, G. Poli and G. Broggini, Intramolecular aminoazidation of unactivated terminal alkenes by palladium-catalyzed reactions with hydrogen peroxide as the oxidant, *Org. Lett.*, 2020, **22**, 1402–1406; (*c*) S. Giofrè, R. Sala, E. M. Beccalli, L. Lo Presti and G. Broggini, Iodoamination of alkenyl sulfonamides by potassium iodide and hydrogen peroxide in aqueous medium, *Helv. Chim. Acta*, 2019, **102**, e1900088; (*d*) T. Borelli, S. Brenna, G. Broggini, J. Oble and G. Poli, (Diacyloxyiodo)benzenes-driven palladium-catalyzed cyclizations of unsaturated *N*-sulfonylamides: opportunities of path selection,

1716 | *Org. Chem. Front.*, 2022, **9**, 1711–1718

This journal is © the Partner Organisations 2022

Adv. Synth. Catal., 2017, **359**, 623–628; (*e*) F. J. S. Duarte, G. Poli and M. J. Calhorda, Mechanistic study of the direct intramolecular allylic amination reaction catalyzed by palladium(II), *ACS Catal.*, 2016, **6**, 1772–1784; (*f*) J. Rajabi, M. M. Lorion, V. Linh Ly, F. Liron, J. Oble, G. Prestat and G. Poli, Dominant versus evolving aminopalladated intermediates: toward a unified mechanistic scenarion in Pd[II]-catalyzed amination, *Chem. – Eur. J.*, 2014, **20**, 1539–1546.

5 (*a*) B. P. Spadafora, F. W. M. Riberio, J. E. Matsushima, E. M. Ariga, I. Omari, P. M. A. Soares, D. de Oliveira-Silva, E. Vinhato, J. S. McIndoe, T. C. Correra and A. Rodrigues, Regio- and diastereoselective Pd-catalyzed aminochlorocyclization of allylic carbamates: scope, derivatization, and mechanism, *Org. Biomol. Chem.*, 2021, **19**, 5595–5606; (*b*) S. T. Nguyen, Q. Zhu and R. R. Knowles, PCET-Enabled olefin hydroamidation reactions with *N*-alkyl amides, *ACS Catal.*, 2019, **9**, 4502–4507; (*c*) H. Yang, G.-T. Fan, L. Zhou and J. Chen, Enantioselective chloro-*O*-cyclization of unsaturated *N*-tosylcarbamates, *Adv. Synth. Catal.*, 2017, **359**, 1295–1300; (*d*) C.-L. Zhu, J.-S. Tian, Z.-Y. Gu, G.-W. Xing and H. Xu, Iron(II)-catalyzed asymmetric intramolecular olefin aminochlorination using chloride ion, *Chem. Sci.*, 2015, **6**, 3044–3050; (*e*) H. Zhu, P. Chen and G. Liu, Pd-Catalyzed intramolecular aminohydroxylation of alkenes with hydrogen peroxide as oxidant and water as nucleophile, *J. Am. Chem. Soc.*, 2014, **136**, 1766–1769; (*f*) D. Huang, X. Liu, L. Li, Y. Cai, W. Liu and Y. Shi, Enantioselective bromoaminocyclization of allyl *N*-tosylcarbamates catalyzed by a chiral phosphine-Sc(OTf)$_3$ c omplex, *J. Am. Chem. Soc.*, 2013, **135**, 8101–8104; (*g*) S. D. R. Christie, A. D. Warrington and C. J. Lunniss, Complemetary reactions of allylic carbamates using palladium(II): formation of oxazolidinones or allylic amides from a common precursor, *Synthesis*, 2009, 148–154; (*h*) E. J. Alexanian, C. Lee and E. J. Sorensen, Palladium-catalyzed ring-forming aminoactoxylation of alkenes, *J. Am. Chem. Soc.*, 2005, **127**, 7690–7691.

6 H. Pan, H. Huang, W. Liu, H. Tian and Y. Shi, Phosphine oxide-Sc(OTf)$_3$ c atalyzed highly regio- and enantioselective bromoaminocyclization of (*E*)-cinnamyl tosylcarbamates. An approach to a class of synthetically versatile functionalized molecules, *Org. Lett.*, 2016, **18**, 896–899.

7 (*a*) A. Kondoh, Y. Kamata and M. Terada, Synthesis of enantioenriched γ-amino-α,β-unsaturated esters utilizing palladium catalyzed rearrangement of allylic carbamates for direct application to formal [3 + 2] cycloaddition, *Org. Lett.*, 2017, **19**, 1682–1685; (*b*) J. Moritz Bauer, W. Frey and R. Peters, Dual palladium(II)/tertriary amine catalysis for asymmetric regioselective rearrangements of allylic carbamates, *Chem. – Eur. J.*, 2016, **22**, 5767–5777; (*c*) J. Moritz Bauer, W. Frey and R. Peters, Asymmetric cascade reaction to allylic sulfonamides from allylic alcohols by palladium (II)/base-catalyzed rearrangement of allylic carbamates, *Angew. Chem., Int. Ed.*, 2014, **53**, 7634–7638, (*Angew. Chem.*, 2014, **126**, 7764–7768); (*d*) D. Xing and D. Yang, Gold(I)-catalyzed highly regio- and stereoselective decarboxylative amination of allylic *N*-tosylcarbamates via base-induced aza-Claisen rearrangement in water, *Org. Lett.*, 2010, **12**, 1068–1071; (*e*) O. V. Singh and H. Han, Iridium(I)-catalyzed stereospecific decarboxylative allylic amidation of chiral branched benzyl allyl imidodicarboxylates, *Org. Lett.*, 2007, **9**, 4801–4804; (*f*) M. E. Synerholm, N. W. Gilman, J. W. Morgan and P. K. Hill, Thermal rearrangement of allylic phenylurethanes, *J. Org. Chem.*, 1968, **33**, 1111–1116.

8 (*a*) M. Chrzanowska, A. Grajewska and M. D. Rozwadowska, Asymmetric synthesis of isoquinoline alkaloids: 2004-2015, *Chem. Rev.*, 2016, **116**, 12369–12465; (*b*) C. Stanciu and T. Penders, Hallucinogen persistent perception disorder induced by new psychoactive substituted phenethylamines, a review with illustrative case, *Curr. Psychiatry Rev.*, 2016, **12**, 221–223; (*c*) B. V. Dean, S. J. Stellpflug, A. M. Burnett and K. M. Engebretsen, 2C or not 2C: phenethylamine designer drug review, *J. Med. Toxicol.*, 2013, **9**, 172–178; (*d*) M. Rodríguez-Mata, V. Gotor-Fernández, J. González-Sabín, F. Rebolledo and V. Gotor, Straightforward preparation of biologically active 1-aryl and 1-heteriarylpropan-2-amines in enantioenriched form, *Org. Biomol. Chem.*, 2011, **9**, 2274–2278; (*e*) M. Vilches-Herrera, J. Miranda-Sepúlveda, M. Rebolledo-Fuentes, A. Fierro, S. Lühr, P. Iturriaga-Vasquez, B. K. Cassels and M. Reyes-Parada, Naphthylisopropylamine and *N*-benzylamphetamine derivatives as monoamine oxidase inhibitors, *Bioorg. Med. Chem.*, 2009, **17**, 2452–2460; (*f*) K. W. Bentley, β-Phenylethylamines and the isoquinoline alkaloids, *Nat. Prod. Rep.*, 2006, **23**, 444–463; (*g*) T. Hasegawa and H. Yamamoto, Development of new chiral auxiliary derived from (*S*)-(-)-phenylethylamine for a synthesis of enantiopure (*R*,)-2-propyloctanoic acid, *Synthesis*, 2003, 1181–1186.

9 Since – in contrast to mesitylene – the variously substituted aromatic reagents do not lend themselves to be used as solvents, and in view of limiting their superstochiometric use, the reactions performed in Table 3 and 4 were carried out in chlorobenzene or dichloroethane, using 5.0 equivalents of the aromatic reagent.

10 C. Michon, F. Medina, F. Capet, P. Roussel and F. Agbossou-Niedercorn, Inter- and intramolecular hydroamination of unactivated alkenes catalysed by combination of copper and silver salts: the unveiling of Brønsted acid catalyst, *Adv. Synth. Catal.*, 2010, **352**, 3293–3305.

11 (*a*) Y.-B. Kang and L. H. Gade, The nature of the catalytically active species in olefin deoxygenation with PhI(OAc)$_2$: metal or proton?, *J. Am. Chem. Soc.*, 2011, **133**, 3658–3667; (*b*) T. T. Dang, F. Boeck and L. Hinterman, Hidden Brønsted acid catalysis: pathways of accidental or delicerate generation of triflic acid from metal triflates, *J. Org. Chem.*, 2011, **76**, 9353–9361; (*c*) M. Tschan, C. M. Thomas, H. Strub and J.-F. Carpentier, Copper(II) triflate as a source of triflic acid: effective, green catalyst of hydroalkoxylation reactions, *Adv. Synth. Catal.*, 2009, **351**, 2496–2504.

12 J. G. Taylor, N. Whittall and K. K. Hii, Copper-catalyzes intermolecular hydroamination of alkenes, *Org. Lett.*, 2006, **8**, 3561–3564.

This journal is © the Partner Organisations 2022

Org. Chem. Front., 2022, **9**, 1711–1718 | **1717**

13 (*a*) M. Sai, Direct synthesis of indanes via iron-catalyzed dehydrative coupling/Friedel-Crafts cyclization of two different alcohols, *Eur. J. Org. Chem.*, 2019, 1102–1106; (*b*) Y. Li, L. Zhang, Z. Zhang, J. Xu, Y. Pan, C. Xu, L. Liu, Z. Li, Z. Yu, H. Li and L. Xu, Regio- and stereoselective synthesis of 1,2,3-trisubstiteted indanes from diarylmethanols and allylamides through iron(III) chloride hexahydrate, *Adv. Synth. Catal.*, 2016, **358**, 2148–2155; (*c*) E. Nomura, Y. Kakimoto, T. Yamamoto, T. Noda, Y. Miyake and H. Mori, Dimerization of ferulic acid and structure determination of phenylindane derivatives, *Res. Chem. Intermed.*, 2016, **42**, 3567–3577; (*d*) O. A. Ivanova, E. M. Budynina, D. A. Skortsov, M. Limoge, A. V. Bakin, A. O. Chagarovskiy, I. V. Trushkov and M. Y. Melnikov, A bioinspired route to indanes and cyclopentannulated hetarenes via, (3 + 2)-cyclodimerization of donor-acceptor cyclopropanes, *Chem. Commun.*, 2013, **49**, 11482–11484; (*e*) V. V. Kouznetsov and D. R. M. Arenas, First green protocols for the large-scale preparation of γ-diisoeugenol and related dihydro (1H) indenes via formal [3 + 2] cycloaddition reactions, *Tetrahedron Lett.*, 2009, **50**, 1546–1549; (*f*) A. R. Katritzky, G. Zhang and L. Xie, Novel route to functionalized indans via formal [3 + 2] cycloadditions of 1-benzylbenzotriazoles with alkenes, *Synth. Commun.*, 1997, **27**, 2467–2478; (*g*) S. R. Angle and D. O. Arnaiz, Formal [3 + 2] cycloaddition of benzylic cations with alkenes, *J. Org. Chem.*, 1992, **57**, 5937–5947.

14 C. L. Ricardo, X. Mo, J. A. McCubbin and D. G. Hall, A surprising substituent effect provides a superior boronic acid catalyst for mild and metal-free direct Friedel-Crafts alkylations and prenylations of neutral arenes, *Chem. – Eur. J.*, 2015, **21**, 4218–4223.

15 (*a*) G. K. Surya Prakash, T. Mathew, C. Panja, A. Kulkarni, G. A. Olah and M. A. Harmer, Tetraflic acid (1,1,2,2-tetrafluoroethanesulfonic acid, $HC_2F_4SO_3H$) and gallium tetraflate as effective catalysts in organic synthesis, *Adv. Synth. Catal.*, 2012, **354**, 2163–2171; (*b*) G. K. Surya, Y. Zhang, L. Chen and T. Lu, A copper(II) triflate-catalyzed tandem Friedel-Crafts alkylation/cyclization process towards dihydroindenes, *Adv. Synth. Catal.*, 2011, **353**, 1055–1060; (*c*) G. A. Olah and A. Molnár, in *Hydrocarbon Chemistry*, John Wiley and Sons, 2003, pp. 160–214; (*d*) M. A. Lanewala and A. P. Bolten, Isomerization of the xylenes using zeolite catalysts, *J. Org. Chem.*, 1969, **34**, 3107–3112; (*e*) R. H. Allem and L. D. Yats, Kinetics of the three-compound equilibrations. II. The isomerization of xylene, *J. Am. Chem. Soc.*, 1959, **81**, 5289–5292; (*f*) H. C. Brown and H. Jungk, The isomerization of *o*- and *p*-xylenes and some related alkylbenzenes under the influence of hydrogen bromide and aluminium bromide; the relative isomerization aptitudes of alkyl groups, *J. Am. Chem. Soc.*, 1955, **77**, 5579–5584; (*g*) D. A. McCaulay and A. P. Lien, Isomerization of the methylbenzenes, *J. Am. Chem. Soc.*, 1952, **74**, 6246–6250.

16 E. J. Eisenbraun, J. R. Mattox, R. C. Bansal, M. A. Wilhelm, P. W. K. Flanagan, A. B. Carel, R. E. Laramy and M. C. Hamming, Polyalkyl aromatic hydrocarbons. II. Cyclialkylation of benzenoid hydrocarbons with isoprene, *J. Org. Chem.*, 1968, **33**, 2000–2008.