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Gold(I)-catalyzed [2 + 2 + 2] cycloaddition of allenamides, alkenes and aldehydes: a straightforward approach to tetrahydropyrans†

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Allenamides participate as two-carbon components in an intermolecular [2 + 2 + 2] cycloaddition with alkenes and aldehydes when treated with catalytic amounts of a phosphite gold complex. The reaction is highly regio- and chemoselective, and works with different types of alkenes, including styrenes, enol ethers or enamides, as well as with aromatic and aliphatic aldehydes. Accordingly, different types of 2,6-disubstituted tetrahydropyrans can be stereoselectively assembled in a single step from commercial or very accessible starting materials.

Introduction

Transition metal catalyzed [2 + 2 + 2] cycloadditions constitute one of the most attractive methodologies for the construction of six-membered cyclic systems.[1] Despite the significant achievements reported in this field, intermolecular examples involving three different cycloaddition partners are extremely scarce, most probably because of the chemo- and regioselectivity issues associated with these multicomponent annulations.[2] The few examples reported so far involve the use of Rh, Ru, Nb or Ni catalysts and at least one alkyne as cycloaddition component.[2] Curiously, and despite the fact that gold catalysis has proven to be very efficient for unveiling novel types of cycloadditions,[3] fully intermolecular [2 + 2 + 2] examples are almost unknown[4] and, to the best of our knowledge, those of three different two-atom components are unprecedented.[5]

Herein, we are pleased to report a fully intermolecular gold-catalyzed [2 + 2 + 2] cycloaddition involving three different π-unsaturated components, namely an allene, an alkene and an aldehyde. The reaction takes place with excellent chemo- and regioselectivity and provides a straightforward and atom-economical entry to tetrahydropyrans (THPs). THPs, and in particular their 2,6-disubstituted counterparts, are privileged scaffolds that are present in a myriad of biologically active molecules (Fig. 1).[6] Although many elegant methods have been developed to construct these motifs,[6,7] none of them encompass the coupling of three readily available components in a single catalytic annulation step.[8]

Over the past few years, we have developed different types of Au-catalyzed annulations,[9] including a cycloaddition between allenamides and oxoalkenes that affords oxabridged medium-sized carbocycles (Scheme 1, eqn (1)).[10,11] This annulation was proposed to proceed through the intermediate **I**,[12] which evolves to the product by the sequential formation of species **II** and **III**. On this basis, we then wondered whether it would be possible to achieve an annulation between the allenamide, alkene and carbonyl units in a fully intermolecular way, a process that would directly afford 2,6-disubstituted THPs like **4** (Scheme 1, eqn (2)). Despite the fact that the process could be viewed as an intermolecular version of the previous annulation, the timely assembly of three different components in a programmed manner is extremely challenging. Indeed, the feasibility of the reaction could be seriously compromised since more simple [2 + 2] adducts of type **5** and **6**,[9c] acyclic products like **7**, or alternative [2 + 2 + 2] adducts (**8**/**9**) could be likewise expected.[13]

Results and discussion

We began our studies by analyzing the reactivity of allenamide **1a** with (*E*)-β-methylstyrene (**2a**) and benzaldehyde (**3a**)

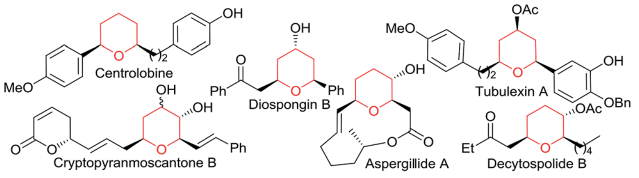

Fig. 1 Tetrahydropyran frameworks in biologically active products.

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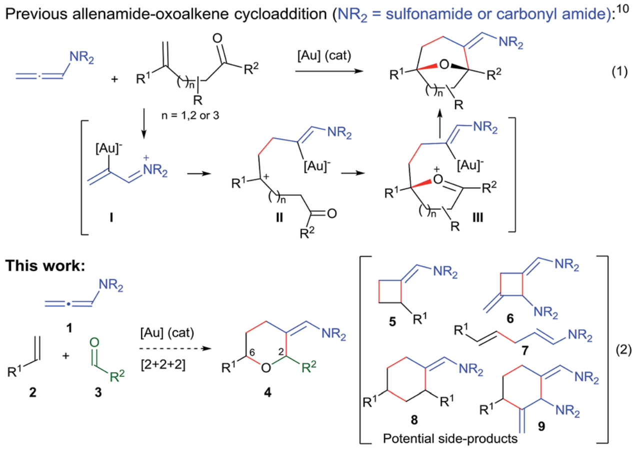


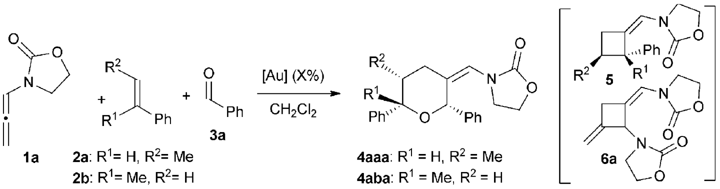
Scheme 1 Previous gold-catalyzed cascade cycloadditions and current proposal.

(Table 1). Initial assays confirmed the expected difficulties for controlling the chemoselectivity of the process. Indeed, despite using an excess of the aldehyde (10 equiv.), and adding the allenamide over 2 hours, the gold complex **Au1** induced the formation of the [2 + 2] allenamide dimerization adduct **6a** in 44% yield, together with a minor amount of the cyclobutane **5aa**,[9c] resulting from the [2 + 2] cycloaddition between **1a** and **2a** (entry 1). A [2 + 2 + 2] adduct, eventually identified as the 2,6-*cis* THP **4aaa**, was also detected, but only in trace amounts. Similarly, other frequently used gold catalysts such as $Ph_3PAuNTf_2$ or the NHC–gold complex **Au2** provided very low yields of the [2 + 2 + 2] adduct **4aaa** (entries 2 and 3), with poor mass recovery balances in all these cases. Interestingly, when using the phosphite-gold complex **Au3**, we observed a significant increase in the global yield of the reaction, which provided **5aa** in 60% yield along with the [2 + 2 + 2] adduct **4aaa** in 21% yield (entry 4). This last yield could be further improved up to 35% by carrying out the reaction at −45 °C (entry 5).[14]

At this point, we envisioned that an additional stabilization of the putative carbocationic species of type **II**, resulting from the addition of the alkene to intermediate **I** (Scheme 1), could eventually facilitate its intermolecular capture by the aldehyde.

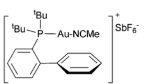
In consonance with this hypothesis, we were pleased to find that the use of α-methylstyrene (**2b**) instead of β-methylstyrene (**2a**) provided, under otherwise identical conditions, the desired THP in an excellent 98% yield, as a 2 : 1 mixture of 2,6-*cis* (**4aba**) and 2,6-*trans* (**4aba′**) diastereoisomers (entry 6).[15] The same result was obtained when **1a** was added in one portion (entry 7). Gold catalysts such as JohnPhosAuNCMeSbF$_6$ (**Au1**), $Ph_3PAuNTf_2$ or IPrAuNCMeSbF$_6$ (**Au2**), also provided the desired [2 + 2 + 2] cycloadduct **4aba** as the major adduct; however, yields and chemoselectivities were significantly lower than those obtained with the phosphite–gold catalyst **Au3** (entry 7 *vs.* 8–10). Moreover, with this latter catalyst the diastereoselectivity could

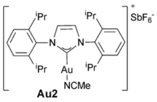
Table 1 Preliminary evaluation of the [2 + 2 + 2] cycloaddition[a,b]

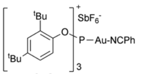


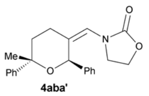
Entry	[Au] (mol%)	**2**	R^1	R^2	Conv.	**4** (%)	**5** (%)	**6** (%)
1	**Au1** (5%)	**2a**	H	Me	99%	**4aaa**, 2	**5aa**, 4	**6a**, 44
2	$Ph_3PAuNTf_2$ (5%)	**2a**	H	Me	60%	**4aaa**, 2	**5aa**, 0	**6a**, 7
3	**Au2** (5%)	**2a**	H	Me	99%	**4aaa**, 15	**5aa**, 7	**6a**, 22
4	**Au3** (2%)	**2a**	H	Me	99%	**4aaa**, 21	**5aa**, 60	**6a**, 8
5[c]	**Au3** (2%)	**2a**	H	Me	99%	**4aaa**, 35	**5aa**, 37	—
6	**Au3** (2%)	**2b**	Me	H	99%	**4aba**, 98[d]	—	—
7[e]	**Au3** (2%)	**2b**	Me	H	99%	**4aba**, 99[d]	—	—
8	**Au1** (2%)	**2b**	Me	H	99%	**4aba**, 51[d]	**5ab**, 17	—
9	$Ph_3PAuNTf_2$ (2%)	**2b**	Me	H	99%	**4aba**, 77[f]	**5ab**, 14	—
10	**Au2** (2%)	**2b**	Me	H	99%	**4aba**, 80[d]	**5ab**, 6	—
11[e,g]	**Au3** (2%)	**2b**	Me	H	99%	**4aba**, 98[h]	—	—
12[e,i]	**Au3** (2%)	**2b**	Me	H	99%	**4aba**, 98[j]	—	—

[a] **1a** (1 equiv.) added over 2 h to a solution of **2** (2 equiv.), **3a** (10 equiv.), [Au] (*X* mol%) and 4 Å MS, in CH_2Cl_2 at −15 °C, unless otherwise noted. [b] Conversion of **1a** and yields of **4–6** determined by ^{1}H-NMR of the crude mixture using 1,3,5-$(MeO)_3C_6H_3$ as internal standard (IS). [c] Carried out at −45 °C, (1 h). [d] Overall yield for the mixture of 2,6-*cis* (**4aba**) and *trans* (**4aba′**); dr = 2 : 1. The major isomer is that drawn. [e] **1a** added in one portion. [f] Overall yield. dr 1.5 : 1. [g] Carried out at −78 °C, (1 h). [h] 90% overall isolated yield, dr 3.5 : 1 (**4aba** : **4aba′**). [i] Carried out in F_3C–Ph at −25 °C (4 h). [j] 86% overall isolated yield, dr 4.5 : 1.


Au1
(JohnPhosAuNCMeSbF$_6$)


Au2
(IPrAuNCMeSbF$_6$)


Au3


4aba'
(minor isomer, entries 6-12)

be improved by either performing the reaction at −78 °C (dr 3.5 : 1, 90% isolated yield, entry 11) or by using α,α,α-trifluorotoluene as solvent (dr 4.5 : 1, 86% yield, entry 12).

With these results in hand, we next analyzed the scope of the process (Table 2). In consonance with the performance of β-methylstyrene (**2a**, Table 1, entry 5), the cycloaddition of styrene (**2c**) with **1a** and benzaldehyde provided the desired 2,6-disubstituted THP (**4aca**) in a moderate 37% yield, but with complete 2,6-*cis* selectivity (**5ac** was also isolated in 45% yield). Gratifyingly, use of styrenes with electron-donating groups (*e.g.* *p*-MeO or *o*-MeO) allowed significant improvement of the chemoselectivity, so the corresponding THPs, **4ada** and **4aea**, were isolated in good yields (60–65% yield) and with complete 2,6-*cis* diastereoselectivity.

On the other hand, the cycloaddition with α-phenylstyrene provided the desired THP (**4afa**) in an excellent 86% yield, whereas the use of *exo*-methylenes such as 1-methylene-tetrahydronaphthalene allowed an efficient access to spirotetrahydropyran derivatives like **4aga**, which was isolated in an excellent 94% yield (dr 1.5 : 1).[16]

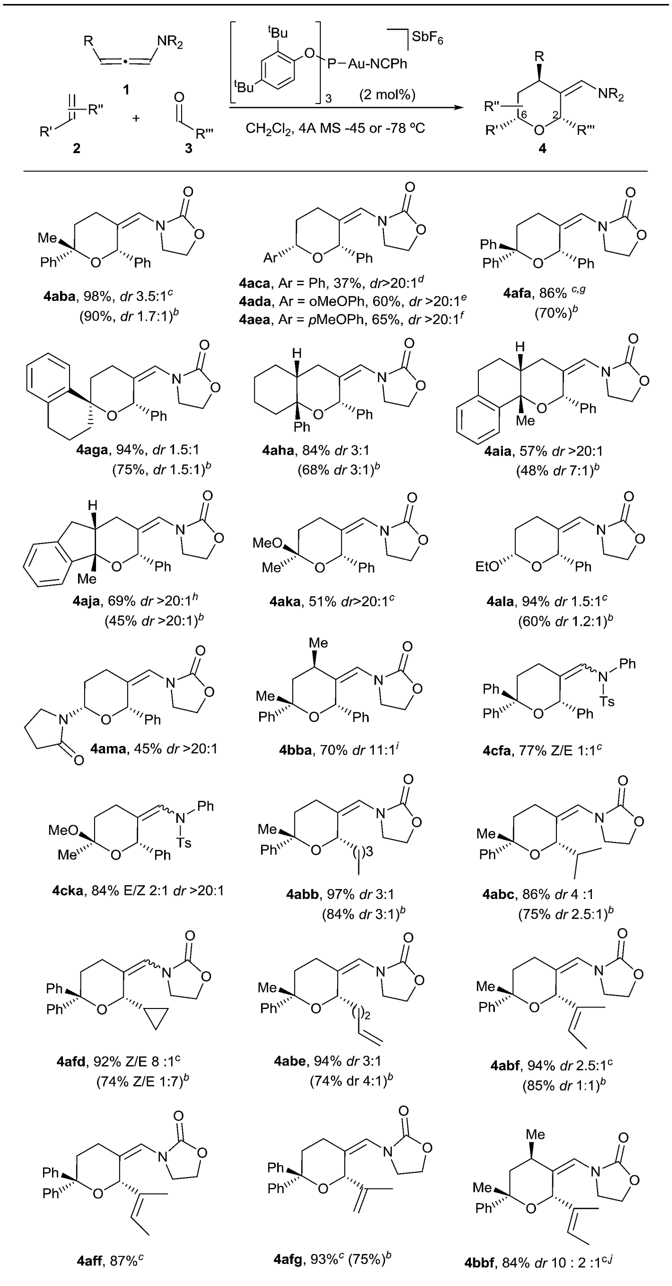
Remarkably, cyclic alkene derivatives were also excellent partners for this process. Thus, the cycloadditions of allenamide **1a** and benzaldehyde with 1-phenylcyclohexene, 4-methyl-1,2-dihydronaphthalene or 3-methyl-1*H*-indene provided the corresponding THPs (**4aha–4aja**) in good yields (57–84% yield) and moderate (**4aha**) or complete (**4aia–aja**) stereoselectivity.[17] X-ray analysis of crystals of **4aha** and **4aia** unambiguously confirmed their structures and relative stereochemistry (Fig. 2).[14]

We next explored the use of alternative electron-rich alkenes. Gratifyingly, the cycloaddition could also be performed with enol ethers such as 2-methoxyprop-1-ene or ethoxyethene, to obtain the corresponding cyclic acetals (**4aka–4ala**) with moderate to good yields. Similarly, the cycloaddition between **1a**, **3a** and 1-vinylpyrrolidin-2-one was also feasible, providing the cyclic hemiaminal ether **4ama** in 45% yield and with complete diastereoselectivity.

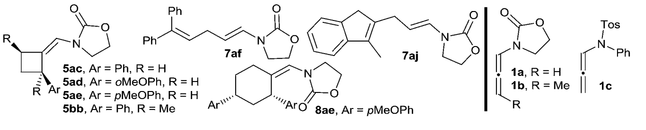
These annulations are also feasible with other allenamides. For instance, the reaction of γ-methyl-substituted allenamide **1b** (see Table 2, footnote) with α-methylstyrene and benzaldehyde provided the [2 + 2 + 2] adduct **4bba**, featuring three new stereogenic centers, in 70% yield and with excellent diastereoselectivity (dr 11 : 1).[18] On the other hand, *N*-tosylphenyl allenamides such as **1c** were also suitable partners. Thus, the [2 + 2 + 2] adduct **4cfa**, resulting from the cycloaddition of **1c**, benzaldehyde and α-phenylstyrene was obtained in 77% yield, whereas the adduct **4cka**, from 2-methoxyprop-1-ene, was obtained in 84% yield and, importantly, with complete stereoselectivity.

Remarkably, the scope of the method is not limited to benzaldehyde. Indeed, the reaction of α-methylstyrene, allenamide **1a** and an aliphatic aldehyde such as pentanal led to the desired adduct, **4abb**, in 97% yield (dr 3 : 1). Other aldehydes such as isobutyraldehyde, cyclopropanecarbaldehyde or pent-4-enal also gave the THPs **4abc–4abe** in excellent yields. α,β-Unsaturated aldehydes such as 2-methylbut-2-enal or methacrolein also participated in the annulation yielding the desired

Table 2 Scope of the Au-catalyzed [2 + 2 + 2] intermolecular cycloaddition[a]



[a] **1** (1 equiv.) added to a solution of **2** (2 equiv.), aldehyde (10 equiv.), [**Au3**] (2 mol%) and 4 Å MS, in CH_2Cl_2 at −45 °C, unless otherwise noted. Conversions >99% (^{1}H-NMR). When a mixture of 2,6-isomers is formed, the major is that drawn. [b] Carried out at −45 °C with a **1**/**2**/**3** molar ratio of 1/1.25/2. [c] Carried out at −78 °C. [d] 45% of **5ac** was also isolated. [e] 21% of **5ad** was also isolated. [f] Traces of **5ae** and **8ae** (5% yield) were also isolated. [g] Traces of **7af** (5% yield) were also isolated. [h] Traces of **7aj** (5% yield) were also isolated. [i] 17% yield of **5bb** was also isolated. [j] For the structure of the minor isomers, see the ESI.



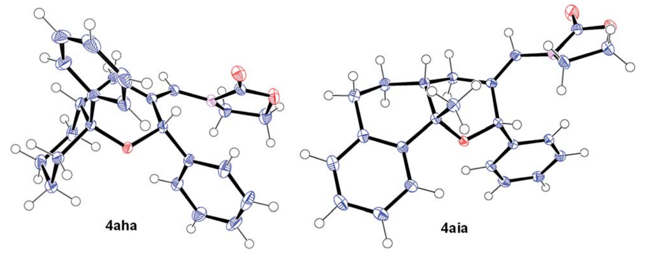


Fig. 2 X-ray structures of **4aha** (left, major isomer) and **4aia** (right).[14]

THPs (**4abf**, **4aff**, **4afg**) in yields above 90%. Moreover, the cycloaddition of the γ-substituted allenamide **1b** with an aliphatic aldehyde such as 2-methylbut-2-enal was also feasible, providing **4bbf** in 84% yield (dr 10 : 2 : 1).[14]

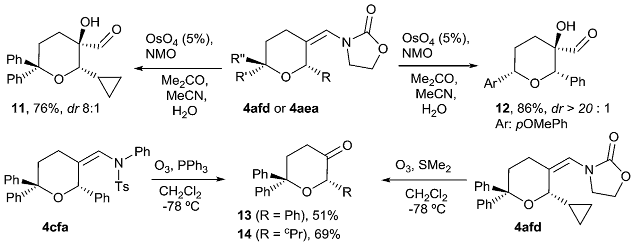
Overall, it is important to highlight that the current method constitutes one of the very few catalytic approaches that affords THPs featuring fully substituted carbons at the oxygen-adjacent position (*e.g.* C6).[19] On the other hand, while the above reactions were carried out using a relatively large excess of the aldehyde, gratifyingly, we found that in most of the cases the reaction can be efficiently performed using an allenamide (**1**)/alkene (**2**)/aldehyde (**3**) molar ratio of 1/1.2/2 (Table 2, footnote *b*, results in parentheses). Thus, using these conditions, THPs **4aba**, **4afa**, **4aga**, **4ala**, **4abb**, **4abc**, **4afd**, **4abe**, **4abf** or **4afg** were obtained in yields varying from 60% to 90% (Table 2).[20] Additionally, more complex polycyclic systems like **4aha–4aja** could also be obtained in yields from 45% to 68%.[14]

We next explored some manipulations of the *exo*-enamide moiety of the products (Scheme 2). Thus, THPs the like **4afd** or **4aea** can be dihydroxylated to afford the α-hydroxo aldehydes **11** and **12** in excellent yields and with very good or complete diastereoselectivity (Scheme 2, eqn (1)). Moreover, both types of enamides (*e.g.* **4afd** and **4cfa**) could be easily converted into their corresponding ketones upon ozonolysis (Scheme 2, eqn (2)).

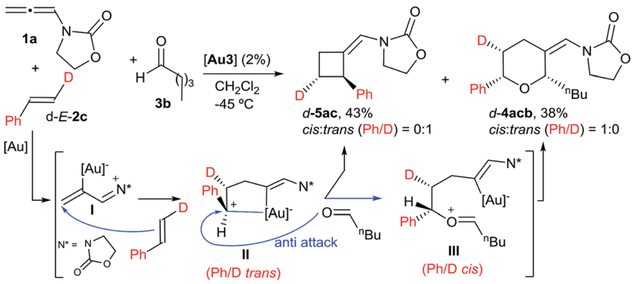
With regard to the mechanism of the annulation, the general proposal indicated in Scheme 1 could also apply for this intermolecular process; however, we found some results that were indicative of a more complex scenario. In particular, it is curious that while the [2 + 2] product (**5aa**) obtained from **1a** and *E*-β-methylstyrene retains the *trans* configuration of the alkene, the [2 + 2 + 2] adduct **4aaa** displays these groups in a *cis* disposition (Table 1, entry 5). On the contrary, polycyclic [2 + 2 + 2] adducts like **4aha**, **4aia** or **4aja** retained the configuration of the parent alkene. To shed light on this divergence, we carried out the cycloaddition of **1a** and pentanal with the *trans*-deuterated styrene d-*E*-**2c** (Scheme 3). As expected, the reaction provided a mixture of the [2 + 2 + 2] and [2 + 2] adducts d-**4acb** (38% yield) and d-**5ac** (43% yield), respectively. Interestingly, d-**5ac** incorporates the Ph and the deuterium atom in a *trans* disposition, whereas the [2 + 2 + 2] adduct, d-**4acb**, holds these groups in a *cis* arrangement. These results strongly suggest the formation of an intermediate of type **II** that preserves the stereochemical information of the alkene due to an stabilizing electrostatic interaction between the gold atom and the benzylic carbocation (Scheme 3).[21] A subsequent nucleophilic *anti* attack of the carbonyl moiety would lead to intermediate **III** and, eventually, to the product d-**4acb**. The preferential formation of this THP with the C2 and C6 substituents in *cis* is in agreement with a transition state that places these groups in equatorial disposition (Prins-like cyclization from **III** to **4**). On the other hand, if species **II** collapses to render a [2 + 2] adduct, the Ph and the D atom would retain the initial *trans* arrangement, as observed in d-**5ac**.

We also analysed the cycloaddition with deuterated α-methylstyrene (d-**2b**) as a model for α-substituted alkenes (Scheme 4). Curiously, the expected [2 + 2 + 2] isomeric adducts d-**4abb** and d-**4abb′** were obtained as mixtures of *cis*/*trans* (Ph/D) isomers. Accordingly, an acyclic carbocation species like **II′** or, alternatively, a fast equilibrium between the Ph/D-*trans* and *cis* intermediates **II** and **II″**, could account for this result.[22,23] Considering this proposal, the exclusive formation of the *cis*-fused polycyclic THPs **4aha–4aja** from cyclic alkene precursors can be also understood.

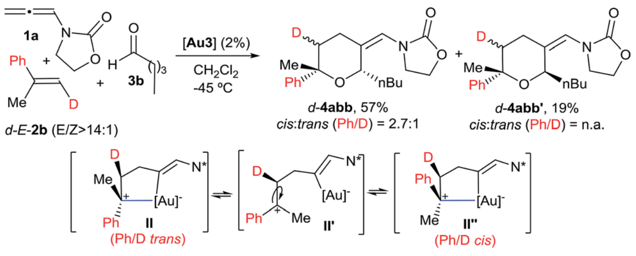
Finally, we carried out the above cycloadditions of Schemes 3 and 4 using the NHC–gold catalyst **Au2**, instead of **Au3**. Not unexpectedly, lower chemoselectivities and yields of the



Scheme 2 Functionalization of the *exo*-enamide moiety.



Scheme 3 Cycloaddition of d-*E*-**2c** and the proposed key intermediate **II**.



Scheme 4 Cycloaddition of d-*E*-**2b** and the proposed key intermediate **II′**.

corresponding [2 + 2 + 2] adducts were obtained in both cases but, interestingly, the stereochemistry of each deuterated cycloadduct (d-**4acb**, d-**5ac** and d-**4abb**), turned out to be identical to that obtained with **Au3**.[14] Thus, the σ-donor or π-acceptor characteristics of the ligand at the gold atom do not seem to significantly affect the nature of the intermediate of type **II**.

Conclusions

In summary, we have developed a gold-catalyzed fully intermolecular [2 + 2 + 2] cycloaddition that constitutes one of the few transition metal catalyzed annulations involving three different π-unsaturated components. The process shows a broad scope with regard to the alkenes and aldehydes that can be used, and provides an efficient, atom-economical and stereoselective access to a variety of 2,6-disubstituted THPs from easily accessible or even commercially available materials.

Acknowledgements

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11 For a review on allenamides, see: T. Lu, Z. Lu, Z. X. Ma, Y. Zhang and R. P. Hsung, *Chem. Rev.*, 2013, **113**, 4862.

12 (*a*) S. Montserrat, H. Faustino, A. Lledós, J. L. Mascareñas, F. López and G. Ujaque, *Chem.–Eur. J.*, 2013, **19**, 15248. See also: (*b*) Y. Horino, Y. Takata, K. Hashimoto, S. Kuroda, M. Kimura and Y. Tamaru, *Org. Biomol. Chem.*, 2008, **6**, 4105; (*c*) M. C. Kimber, *Org. Lett.*, 2010, **12**, 1128.

13 (*a*) [2 + 2] adducts of type **5** and **6** were previously reported, see ref. 9*c*; For addition products related to **7**, see; (*b*) A. W. Hill, M. R. Elsegood and M. C. Kimber, *J. Org. Chem.*, 2010, **75**, 5406.

14 See the ESI† for further details.

15 (*a*) The [2 + 2] adducts **5ab**, **6a**, or other side-products, were not detected in the crude mixture (^{1}H-NMR); (*b*) The structure and relative stereochemistry of both THP isomers (**4aba**/**4aba′**) were established by NMR and, additionally, those of the major isomer (**4aba**), with the Ph groups in *cis*, were further confirmed by X-ray ESI.† [14]

16 When a diastereoisomeric mixture is formed in the reactions of Table 2, the 2,6-*cis* and *trans* isomers could usually be separated by standard chromatography. ESI.†

17 The ring fusion was exclusively *cis* in all these polycyclic systems. Therefore, dr refers to the substituents at the 2,6-THP positions.

18 An α-alkyl-substituted allenamides such as 3-(buta-2,3-dien-2-yl)oxazolidin-2-one provided a complex mixture of products.

19 (*a*) Previously reported approaches are essentially limited to the formation of THPs with monosubstituted C2 or C6

carbons,[6a] something that significantly facilitates a high stereoselection; For isolated catalytic examples yielding products with fully substituted-C2 or C6 carbons, see: (*b*) M. Jacolot, M. Jean, N. Levoin and P. van de Weghe, *Org. Lett.*, 2012, **14**, 58; (*c*) M. P. Castaldi, D. M. Troast and J. A. Porco Jr, *Org. Lett.*, 2009, **11**, 3362; (*d*) J. S. Yadav, B. V. Subba Reddy, G. G. K. S. Narayana Kumar and S. Aravind, *Synthesis*, 2008, 395.

20 **4aba** can even be obtained using a 1 : 1 : 1 ratio (86% yield, dr 1.8 : 1).

21 (*a*) A. Z. Gonzalez, D. Benitez, E. Tkatchouk, W. A. Goddard and F. D. Toste, *J. Am. Chem. Soc.*, 2011, **133**, 5500; (*b*) See also ref. 12*a*.

22 The preferential formation of the THP **4abb**, is also in agreement with a preferred Prins-like transition state that holds the bulkier groups at C2 and C6 in equatorial disposition.

23 Similarly, the cycloaddition of an electron-rich styrene such as *trans*-deuterated *p*-methoxystyrene (d-*E*-**2e**) with **1a** and benzaldehyde provided d-**4aea** (64% yield) and traces of the [2 + 2] adduct d-**5ae**, both as almost equimolar mixtures of *cis* and *trans* (*p*MeOPh/D) isomers.[14] Thus, an intermediate of type **II**′ (or an equilibrium between the *cis* and *trans* cyclic isomers **II**, Scheme 4) might also operate in this case.