

Short communication

## Design of CO<sub>2</sub> hydrogenation catalysts based on phosphane/borane frustrated Lewis pairs and xanthene-derived scaffolds

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## ABSTRACT

New naphtho[2,1,8,7-klmn]xanthene and benzo[*kl*]xanthene-based intramolecular phosphane–borane frustrated Lewis pairs (FLPs) were investigated in catalyzed H<sub>2</sub> activation and CO<sub>2</sub> hydrogenation processes. According to DFT predictions at the B3LYP-D3 level, the presence of rigid scaffolds and increased P...B distances in the investigated FLPs lead to a remarkable drop in the energy barrier for CO<sub>2</sub> hydrogenation (by up to 19.2 kcal mol<sup>-1</sup>, compared to the parent dimethylxanthene-based FLP). Furthermore, the energy differences between the transition states for H<sub>2</sub> activation and CO<sub>2</sub> hydrogenation are significantly reduced, making both processes feasible under relatively mild experimental conditions.

## 1. Introduction

The class of catalysts known as Frustrated Lewis Pairs (FLP) have received great attention since the first report by D-W Stephan *et al.* in 2006 [1]. In general, they are defined as Lewis acid-base pairs unable to form conventional Lewis adducts due to steric hindrance of their structure. A broader definition for FLP chemistry has also been commonly used [2]. The versatility of possible structures and their catalytic properties makes them potential candidates to replace metal-based catalysts in greener chemical processes [3,4]. Despite their promising catalytic properties, side-reactions and self-deactivation of these catalysts remain a great challenge to be overcome before large scale applications are possible. The key for higher efficiency and selectivity of FLPs lies in the identification of electronic and structural factors capable of fine tuning the reactivity and stability of these systems [5].

Amongst the most promising strategies for dealing with these challenges, the preparation of new intramolecular FLP systems supported by distinct backbones is an alternative for tailoring more efficient systems, beyond the conventionally investigated changes in steric repulsion and electronic effects of substituents. The pioneering work of Erker *et al.* has shown four-membered cyclic intramolecular phosphane–borane (P/B)

adducts (vicinal FLPs, Fig. 1i) capable of catalyzing rapid H<sub>2</sub> splitting at room temperature and low H<sub>2</sub> pressure [6]. Other relevant examples of scaffolds for supporting FLPs are carbon atoms/chains as spacer (*e.g.* geminal [7] and vicinal [8] FLPs), phenylenes [9], naphthalenes [10], biphenylenes [11], dibenzofurans [12], macrocycles [13], and molecular cages [14], together with a range of modifications of distinct substituent groups that confer electron withdrawing/releasing effects onto the acid-base units of the resulting FLPs (Fig. 1i).

Recently, Mo and Aldridge [12] have shown how the use of the dimethylxanthene backbone to prevent intramolecular-type P/B interactions can lead to preorganized FLPs and tuned activity towards reversible activation of H<sub>2</sub> molecules (1, Figure 1ii) [12]. As well as the structural effect, these authors also showed that with strongly donating alkyl-substituted phosphine components the hydrogenation reaction becomes irreversible (2, Figure 1ii) [12] and that unsubstituted alkyl (phenyl) groups cause a reduction of the FLP activity (3, Figure 1ii) [15]. On the other hand, the absence of electron withdrawing groups on B resulted in the quenching of the activity of these derivatives for H<sub>2</sub> splitting (4, Figure 1ii) [15]. These derivatives were used in a wide range of applications, such as dihydrogenation of amine-boranes [15], C (sp)-H bond activation [16] and N<sub>2</sub>O capture [12].

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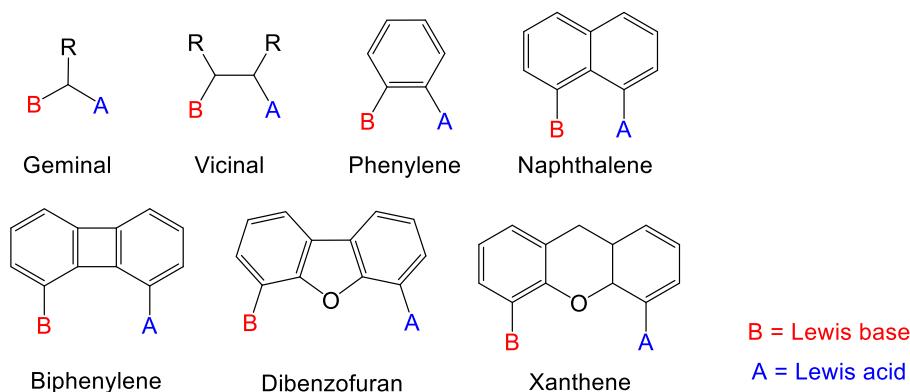
Motivated by the catalytic activity of xanthene-containing derivative **1a**, we have now applied density functional theory (DFT) to explore new xanthene-inspired scaffolds as backbones for intramolecular P/B FLPs, namely tribenzo[*b,d,f*]oxepine, naphtho[2,1,8,7-*klmn*]xanthene, and benzo[*kl*]xanthene (Figure 1iii). Such structures were selected in order to probe how changes in the flexibility/rigidity of the linker bearing the Lewis acid and base units can affect the P...B interaction and, in particular, the reactivity towards H<sub>2</sub> activation and the subsequent CO<sub>2</sub> hydrogenation reaction to produce formic acid, which is a key step for the development of new catalysts for conversion of CO<sub>2</sub> into added-value chemicals, with potential applications in many industrial processes, from solvents and reactants production, to liquid fuel synthesis. [17] Generally, CO<sub>2</sub> hydrogenation has been thoroughly investigated in the context of heterogeneous catalysts [17]. Only recently examples of homogenous catalysts have been reported to be active for this reaction; however they are commonly formed by efficient, but expensive, noble metal complexes [18–20], or organic catalysts (including FLPs), which require harsh conditions, long reaction times, and/or lead to stoichiometric reactions [21–26]. In contrast, the new FLP systems proposed

here prove to be potential candidates for applications in catalytic H<sub>2</sub> activation and CO<sub>2</sub> hydrogenation under relatively mild reaction conditions.

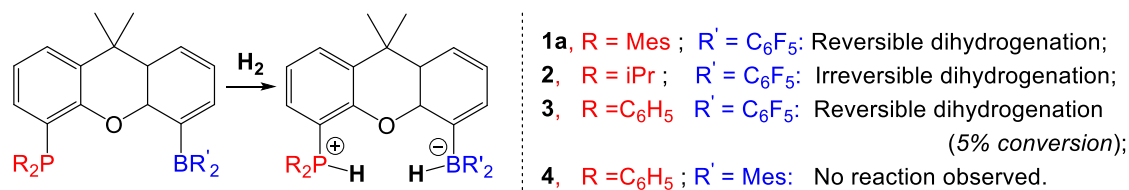
## 2. Results and discussion

Parent derivative **1a** was first analysed regarding its structure and reactivity. A key parameter commonly used in the rationalisation of the reactivity of FLPs is the interatomic distance between their acid and base units. As shown in Fig. 2a, **1a** presents a P...B interatomic distance of  $r_{B...P} = 3.871 \text{ \AA}$ . This distance is linked to the “hinge angle” at the central 4*H*-pyran moiety and can be modified through breathing (or wing-flapping) motion of the xanthene backbone. We assess this structural feature through the angle  $\phi$  between the two aryl rings of the xanthene moiety, where  $\phi = 180^\circ$  implies perfect co-planarity (see Supporting Information for definition of  $\phi$ ). Interestingly, when acting as catalyst in H<sub>2</sub> activation, and consecutively in the CO<sub>2</sub> hydrogenation to produce formic acid (Fig. 2b),  $r_{B...P}$  and  $\phi$  change significantly during binding or activation of the reactants, as is evident in the transition state structure

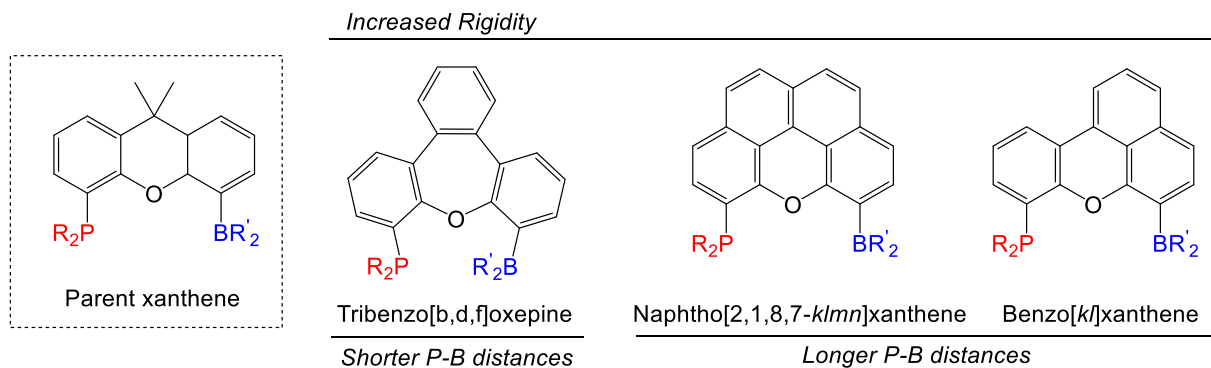
### i. Selected examples of intramolecular FLPs



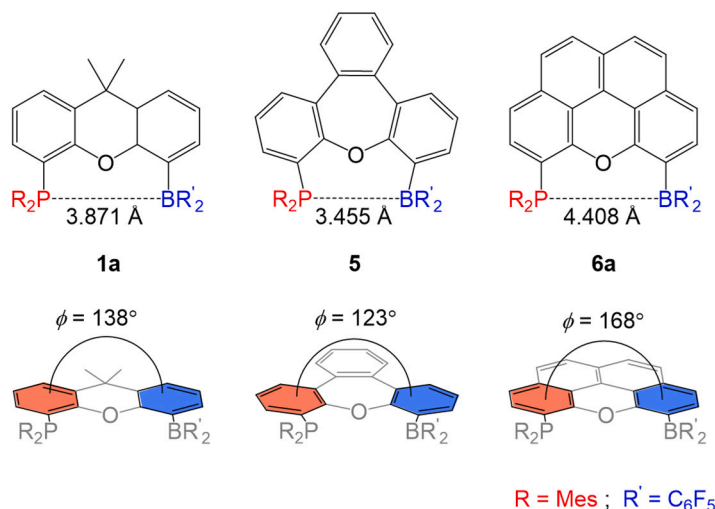
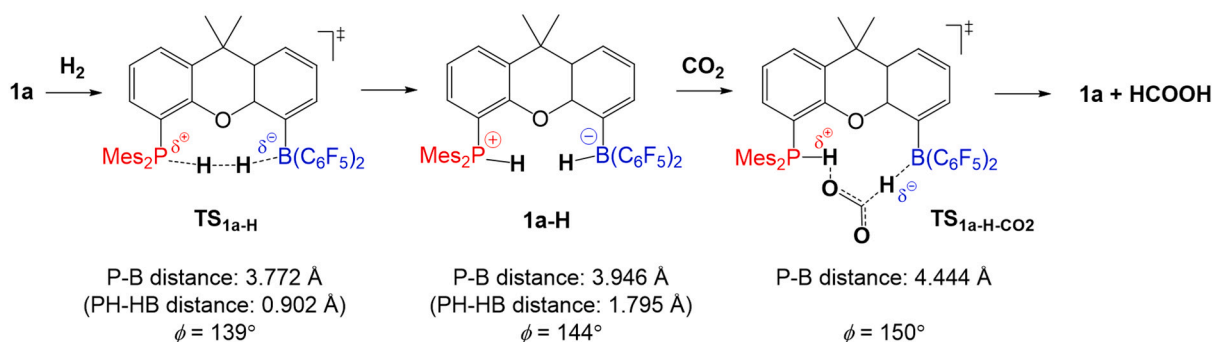
### ii. Reactivity of dimethylxanthene-derived P/B FLPs



### iii. This work:



**Fig. 1.** (i) Commonly used scaffolds for the construction of intramolecular FLPs, (ii) previously reported reactivity of dimethylxanthene-based P/B FLPs in H<sub>2</sub> activation reaction, and (iii) proposed modifications of the xanthene-based backbone of P/B FLPs investigated in this work.

a. Selected structural parameters of catalysts **1a**, **5**, and **6a**:b. Optimized structure of stationary points along the PES of  $\text{CO}_2$  hydrogenation reaction catalyzed by **1a**:

Method: CPCM(bromobenzene) B3LYP-D3/6-311+G\*(\*)//M06-2X/6-31G\*(\*)

**Fig. 2.** (a) P...B interatomic distances (Å) and angles (degrees) between P- and B-containing aryl rings of derivatives **1a**, **5**, and **6a**, and (b) of derivative **1a** throughout the catalyzed  $\text{CO}_2$  hydrogenation reaction. Angle between the aryl rings on the xanthene backbone was calculated according to the procedure described in subsection 2 of Supporting Information.

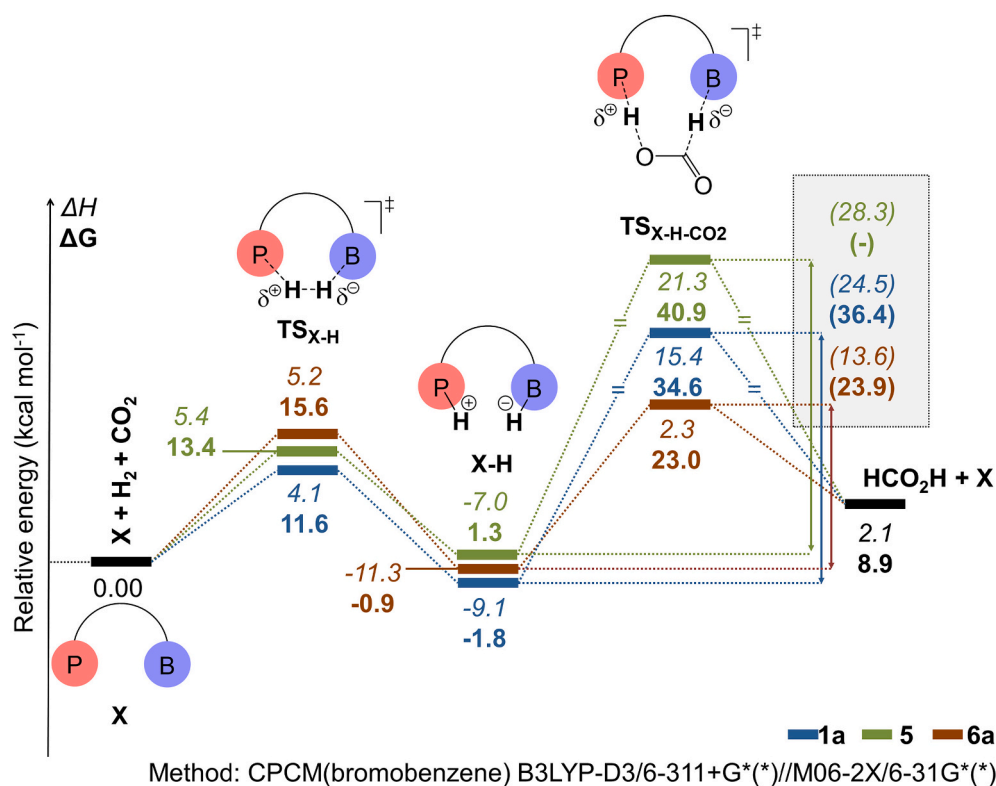
for the  $\text{CO}_2$  hydrogenation step (**TS<sub>1a-H-CO2</sub>**), in which  $r_{B...P}$  and  $\phi$  increase by 0.573 Å and  $12^\circ$ , respectively, when compared to the isolated catalyst, **1a**. For the hydrogenation step (**TS<sub>1a-H</sub>**), the structural changes of the dimethylxanthene backbone are less significant. However, it is still worth mentioning that the P...B distance is slightly reduced to facilitate the H-H bond cleavage (**TS<sub>1a-H</sub>**, Fig. 2b).

The full energy profile for  $\text{CO}_2$  hydrogenation catalyzed by **1a** is shown in Fig. 3. The calculated Gibbs free-energy barrier for  $\text{H}_2$  activation is  $11.6 \text{ kcal mol}^{-1}$ , whereas the calculated barrier for the  $\text{CO}_2$  hydrogenation step is  $34.6 \text{ kcal mol}^{-1}$ . Experimental studies showed that  $\text{H}_2$  is readily activated by **1a** under mild reaction conditions -  $\text{H}_2$  (1 atm),  $22^\circ\text{C}$ , in  $\text{C}_6\text{D}_5\text{Br}$ , in agreement with the relative low energy barrier calculated here for such a process [12]. No experimental data are available regarding the  $\text{CO}_2$  hydrogenation step catalyzed by **1a**. Nevertheless, the computed differences in the free energy barrier of  $23.0 \text{ kcal mol}^{-1}$  (an increase in enthalpy of  $20.4 \text{ kcal mol}^{-1}$ ) compared to the previous step indicates that such process would not occur under similar experimental conditions. Similar high energy barriers for  $\text{CO}_2$  hydrogenation have been reported for other classes of intramolecular P/B FLPs [27]. Finally, the computed reaction energy shows this to be an endothermic and endergonic process ( $\Delta H_R = +2.1 \text{ kcal mol}^{-1}$ ,  $\Delta G_R = +8.9 \text{ kcal mol}^{-1}$ ) in agreement with previous reports [28–30].

Based on the observations of shortening and increasing of the P...B

interatomic distances observed for **1a** during  $\text{H}_2$  activation and  $\text{CO}_2$  hydrogenation processes, respectively, two new prototypic scaffolds were investigated: tribenzo[*b,d,f*]oxepine (**5**) and naphtho[2,1,8,7-*klmn*]xanthene (**6a**) backbones (Fig. 2). Both were constructed using mesitylene (–Mes) and pentafluorophenyl (– $\text{C}_6\text{F}_5$ ) substituents bonded to the P and B moieties, respectively, to allow direct comparison of their catalytic activity against that of the parent catalysts, **1a**. The optimized structures of **5** and **6a** have  $r_{B...P} = 3.445 \text{ Å}$  and  $4.408 \text{ Å}$ , respectively. Effectively, these represent a shortening of the P...B distance by  $0.416 \text{ Å}$  for **5** and an increase by  $0.537 \text{ Å}$  for **6a**, when compared to **1a**. The angle between the aromatic rings holding the P and B units also changed significantly for these derivatives, with calculated values of  $138^\circ$ ,  $123^\circ$ , and  $168^\circ$  for **1a**, **5**, and **6a**, respectively (Fig. 2). When these new FLPs were tested for their putative catalytic activity in  $\text{H}_2$  activation (step 1, Fig. 3), both showed a slight increase in the calculated activation energy, in comparison to **1a** - an increase in the free energy barrier by  $+1.8$  and  $+4.0 \text{ kcal mol}^{-1}$  for **5** and **6a**, respectively; even smaller if the enthalpies are calculated. In contrast, the subsequent energy barrier for the  $\text{CO}_2$  hydrogenation step is significantly affected for the two FLPs, **5** and **6a**, as discussed next.

At this point, it is worth mentioning that in most cases investigated here, the calculated reaction energies for formation of the hydrogenated intermediate **X-H** showed this to be an exothermic and exergonic



**Fig. 3.** Energy profile for H<sub>2</sub> activation and CO<sub>2</sub> hydrogenation catalyzed by the Frustrated Lewis Pairs X (X = **1a**, **5** and **6a**). Relative enthalpies (*italic*) and Gibbs free energy (**bold**) were calculated by taking the isolated reactants as reference. Energy differences between points X-H and TS<sub>X-H-CO<sub>2</sub></sub> are given in parenthesis for the cases in which this is the rate-determining step.

process (e.g. **1a-H** and **6a-H**, Fig. 3). For these cases, intermediate X-H is the resting stage of the catalytic mechanism; thus it should be considered in the calculation of the energy barrier for the CO<sub>2</sub> hydrogenation step, in accordance with the Energy Span Model conceptualised by Kozuch and Shaik [31,32]. Accordingly, the energy difference between points X-H and TS<sub>X-H-CO<sub>2</sub></sub> are also given in Fig. 3. For **5**, however, formation of X-H was computed as a slightly endergonic process, although the enthalpy change still showed this to be exothermic (e.g. **5-H**, Fig. 3). In this case, the resting state on the catalytic cycle is that with the isolated reactants, and the free energy barrier for CO<sub>2</sub> hydrogenation step is the same as the relative energy of the corresponding transition state structure TS<sub>X-H-CO<sub>2</sub></sub>; when comparing enthalpies, the energy difference between points X-H and TS<sub>X-H-CO<sub>2</sub></sub> should still be considered. For predictions concerning the energy span under turnover conditions, the endothermicity and endergonicity of the overall catalytic process also need to be taken into consideration, *i.e.* the energy span under turnover conditions is determined by the energy barrier for the CO<sub>2</sub> hydrogenation step, as discussed above, summed to the calculated reaction energy variations ( $\Delta H_R = +2.1$  kcal mol<sup>-1</sup> and  $\Delta G_R = +8.9$  kcal mol<sup>-1</sup>, Fig. 3). Nevertheless, as the latter remains unaltered for all investigated systems, the comparison of the changes in the energy barrier for individual steps of the catalytic process suffice to rationalise the catalytic activities studied here. Later on, the same approach will be used for the results presented in Table 1.

Taking into consideration the points discussed above, while the CO<sub>2</sub> hydrogenation step catalyzed by **5** led to a +4.5 kcal mol<sup>-1</sup> increase in the calculated activation free energy (+3.8 kcal mol<sup>-1</sup> for enthalpy, Fig. 3), catalyst **6a** led to a notable reduction of -12.5 kcal mol<sup>-1</sup> in the activation free energy (-10.9 kcal mol<sup>-1</sup> for enthalpy, Fig. 3). Therefore, while the large P...B distance in **6a** and the rigid nature of its backbone structure led to an increase in the activation energy for step 1, in contrast, such features led to substantial reduction in the activation energy for step 2. As the activation energy for step 2 is higher than that

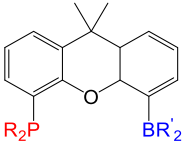
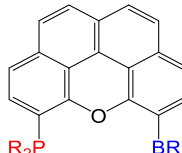
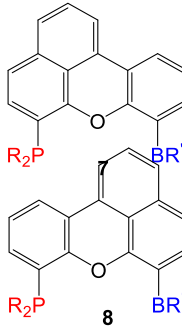
for step1, which itself is relatively low, the general effect is a reduction in the activation energy for the whole process. In addition, we considered possible effects from using solvents with different polarities for selected FLPs. Repeating the single-point energy calculations in the gas phase (as ultimate limit for nonpolar solvents) and in a continuum using the parameters of DMSO (a highly polar solvent) raises and lowers, respectively, the relative energies of both intermediate X-H and transition state TS<sub>X-H-CO<sub>2</sub></sub> when the energy of the isolated reactants are taken as reference. However, for both the key difference is affected only to a small extent (up to 2.6 kcal mol<sup>-1</sup>, see Table S2, Supporting Information).

Next, we explored modifications in substituents R and R' in **1a** and **6a**, in an attempt to achieve further reduction in the activation energy for the CO<sub>2</sub> hydrogenation step. The effects of electron-withdrawing or electron-releasing groups were evaluated by two approaches: (i) by replacing the pentafluorophenyl (-C<sub>6</sub>F<sub>5</sub>) group by a 3,5-bis(trifluoromethyl)phenyl (-Ph(CF<sub>3</sub>)<sub>2</sub>) substituent at the B moiety, reducing the Lewis acidity of the borane; (ii) by replacing the mesitylene (-Mes) group by a 1,3-diisopropyl-5-methyl-phenyl (-DIMP) substituent at the P moiety, to verify the electron-donating effects of alkyl substituents on the basicity of the phosphane. Although an extensive list of potential modifications to FLPs could be proposed based on previous experimental and computational studies, [3-5] the resulting electronic effects reported before are similar to the ones investigated here. Furthermore, when compared to the distinct FLP backbones investigated here, changes in the electron realising/withdrawing abilities of substituents groups are expected to have a less significant effect over the calculated energy barriers, as will be discussed next.

The calculated energy data for these new FLP catalysts is given in Table 1. The calculated free energy barrier for H<sub>2</sub> activation catalyzed by dimethylxanthene-based FLPs (**1a-1d**, Table 1) ranged from 11.6 to 16.5 kcal mol<sup>-1</sup> (from 3.9 to 6.7 kcal mol<sup>-1</sup> if enthalpy is considered). The lowest barrier for this step is observed for **1a**, whereas **1c** has the

**Table 1**

Relative energy for H<sub>2</sub> activation and CO<sub>2</sub> hydrogenation catalyzed by X (a, X = **1a**, **1b**, **1c**, and **1d**; b, X = **6a**, **6b**, **6c** and **6d**; c, X = **7** and **8**). The relative energies (kcal mol<sup>-1</sup>) were calculated by taking the energy of the isolated reactants as reference. Values in parentheses are the relative energies between points X-H and TS<sub>X-H-CO<sub>2</sub></sub> ( $\Delta\Delta E$  (X-H, TS<sub>X-H-CO<sub>2</sub></sub>)) for the cases in which this is the rate-determining step.

a. Dimethylxanthene-based P/B FLPs								
	R	R'		TS <sub>X-H</sub>	X-H	TS <sub>X-H-CO<sub>2</sub></sub>	$\Delta\Delta E$ (X-H, TS <sub>X-H-CO<sub>2</sub></sub> )	
	<b>1a</b>	Mes	C <sub>5</sub> F <sub>6</sub>	$\Delta H$	4.1	-9.1	15.4	-24.5
				$\Delta G$	11.6	-1.8	34.6	-36.4
	<b>1b</b>	DIMP	C <sub>5</sub> F <sub>6</sub>	$\Delta H$	3.9	-10.6	9.8	-20.4
				$\Delta G$	13.9	-1.6	32.5	-34.1
	<b>1c</b>	Mes	Ph(CF <sub>3</sub> ) <sub>2</sub>	$\Delta H$	6.7	-4.0	14.9	-18.9
			$\Delta G$	16.5	2.1	35.1	(-)	
	<b>1d</b>	DIMP	Ph(CF <sub>3</sub> ) <sub>2</sub>	$\Delta H$	4.5	-4.9	18.4	-23.3
			$\Delta G$	13.2	3.6	39.0	(-)	
b. Naphtho[2,1,8,7-klmn]xanthene-based P/B FLPs								
	R	R'		TS <sub>X-H</sub>	X-H	TS <sub>X-H-CO<sub>2</sub></sub>	$\Delta\Delta E$ (X-H, TS <sub>X-H-CO<sub>2</sub></sub> )	
	<b>6a</b>	Mes	C <sub>5</sub> F <sub>6</sub>	$\Delta H$	5.2	-11.3	2.3	-13.6
				$\Delta G$	15.6	-0.9	23.0	-23.9
	<b>6b</b>	DIMP	C <sub>5</sub> F <sub>6</sub>	$\Delta H$	6.7	-13.4	-0.3	-13.1
				$\Delta G$	16.2	-3.6	21.4	-25.0
	<b>6c</b>	Mes	Ph(CF <sub>3</sub> ) <sub>2</sub>	$\Delta H$	7.7	-3.0	3.1	-6.1
			$\Delta G$	15.0	3.1	23.0	(-)	
	<b>6d</b>	DIMP	Ph(CF <sub>3</sub> ) <sub>2</sub>	$\Delta H$	6.8	-11.1	0.2	-11.3
			$\Delta G$	13.5	3.8	17.2	(-)	
c. Benzo[kl]xanthene-based P/B FLPs								
	R	R'		TS <sub>X-H</sub>	X-H	TS <sub>X-H-CO<sub>2</sub></sub>	$\Delta\Delta E$ (X-H, TS <sub>X-H-CO<sub>2</sub></sub> )	
	<b>7</b>	DIMP	Ph(CF <sub>3</sub> ) <sub>2</sub>	$\Delta H$	6.8	-11.5	2.7	-14.2
				$\Delta G$	16.3	-1.6	22.2	-23.8
	<b>8</b>	DIMP	Ph(CF <sub>3</sub> ) <sub>2</sub>	$\Delta H$	6.0	-9.5	2.4	-11.9
			$\Delta G$	14.6	0.1	22.4	(-)	

Method: CPCM(bromobenzene) B3LYP-D3/6-311+G\*(\*)//M06-2X/6-31G\*(\*)

highest enthalpy and free energy barrier in the set. Conversely, **1a** and **1c** led to the highest (24.5 kcal mol<sup>-1</sup>) and the lowest (18.9 kcal mol<sup>-1</sup>) activation enthalpy for the CO<sub>2</sub> hydrogenation step, respectively.

Similar energy ranges were observed for naphtho[2,1,8,7-klmn]xanthene-based FLPs (**6a-6d**, Table 1). The derivative bearing the -Mes and -Ph(CF<sub>3</sub>)<sub>2</sub> substituents (**6c**) was calculated to have the lowest activation enthalpy for CO<sub>2</sub> hydrogenation (6.1 kcal mol<sup>-1</sup>) at the expense of a slight increase in the activation enthalpy for H<sub>2</sub> activation (7.7 kcal mol<sup>-1</sup>). Remarkably, **6c** has an enthalpy profile in which the rate determining step is the H<sub>2</sub> activation and not the CO<sub>2</sub> hydrogenation step. When free energies are considered, derivative **6d** presented the lowest barriers, 13.5 kcal mol<sup>-1</sup> for step 1 and 17.2 kcal mol<sup>-1</sup> for step 2.

In order to verify the effect of the rigidity of derivatives **6a-6d** on the activation energy for CO<sub>2</sub> hydrogenation, two additional FLP models were designed by using a benzo[kl]xanthene backbone: derivatives **7** and **8** (Table 1), both bearing -DIMP and -Ph(CF<sub>3</sub>)<sub>2</sub> substituents. The absence of one fused benzene ring in their structure resulted in a slight increase in the free energy barrier for H<sub>2</sub> activation (by 3.0 and 1.1 kcal mol<sup>-1</sup> for **7** and **8**, respectively) when compared to **6d**. On the other hand, a more significant change was observed in the free energy barrier of the CO<sub>2</sub> hydrogenation step, which increased by 6.6 and 5.2 kcal mol<sup>-1</sup> for **7** and **8**, respectively. Still, these energy barriers are significantly smaller than those obtained for the parent FLP **1a**.

Finally, it should be noted that catalysts for CO<sub>2</sub> hydrogenation

should also be potent catalysts for the reverse reaction, *i.e.*, dehydrogenation of formic acid. In fact, for complex **6d**, the barrier for this process (forming **6d-H** under liberation of CO<sub>2</sub>) is computed to be just 8.3 kcal mol<sup>-1</sup>, that for H<sub>2</sub> release to regenerate **6d** is only slightly higher, 9.8 kcal mol<sup>-1</sup> (see data in Table 1). Ruthenium-based complexes have been developed for this purpose, with potential use in powering fuel cells with H<sub>2</sub> produced from formic acid as fuel [33,34]. In the spirit of the 2021 Nobel prize in chemistry for organocatalysis [35], FLPs of the type we have identified could be greener and cheaper alternatives to these toxic and expensive heavy-metal catalysts. An additional advantage of FLPs in practical applications could be that once immobilized through covalent attachment to a solid support, catalyst recovery should be easy, without any danger of metal leaching.

### 3. Conclusions

For the intramolecular P/B FLPs containing the rigid naphtho[2,1,8,7-klmn]xanthene and benzo[kl]xanthene backbones, we predict a remarkable reduction in the activation energy for CO<sub>2</sub> hydrogenation, at the expense of slight increase in the preliminary H<sub>2</sub> activation step, compared to the parent dimethylxanthene-based FLP **1a**. For the new FLPs designed in this work, the lowest calculated free energy barrier for CO<sub>2</sub> hydrogenation is 17.2 kcal mol<sup>-1</sup> (*ca.* 26 kcal mol<sup>-1</sup> under turnover). These are, to the best of our knowledge, the first examples of xanthene-inspired intramolecular P/B FLPs with potential to allow

kinetically accessible H<sub>2</sub> activation and subsequent CO<sub>2</sub> hydrogenation processes under relatively mild reaction conditions. These FLPs are also predicted to be promising candidates for catalyzing the reverse process, namely H<sub>2</sub> release from formic acid.

### Declaration of competing interest

There are no conflicts to declare.

### Acknowledgements

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.catcom.2021.106385>.

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