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# Endocyclic Enamides Derived from Aza-Diketopiperazines as Olefin Partners in Povarov Reaction: An Access to Tetracyclic N-Heterocycles

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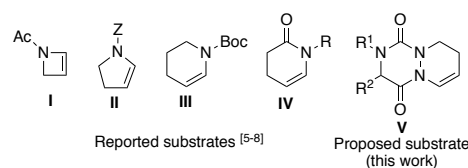
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Supporting information for this article (computational data and NMR spectra) is given via a link at the end of the document.

**Abstract:** Original endocyclic enamides based on a bicyclic aza-diketopiperazine (aza-DKP) structure have been used as dienophile partners in the Povarov reaction. The reported method represents a successful strategy for the structural diversification of the aza-DKP scaffold, giving access to a new family of fused tetracyclic N-heterocycles, which contain at least four nitrogen atoms in the heterocyclic structure. Depending on the nature of the aldehyde partner, the cycloadditions have been performed either as a two-component or a three-component reaction (2CR or 3CR), in the presence of BF<sub>3</sub> as a Lewis acid catalyst. With aliphatic aldehydes the reaction proceeds with high diastereoselectivities in favor of the cis compounds. Some mechanistic aspects of this cycloaddition have been examined computationally.

the Povarov reaction. However, they represent attractive substrates to access various N-polyheterocycles of pharmaceutical interest. In Figure 1 are illustrated the few published examples of 4-,<sup>[5]</sup> 5-,<sup>[6]</sup> and 6-membered ring<sup>[7]</sup> endocyclic enamides or enecarbamates **I-III**, and 6-membered ring unsaturated lactams derivatives **IV**.<sup>[8]</sup> In this context, we decided to investigate the aza-diketopiperazine (aza-DKP) derivative represented by the general structure **V**, as a new type of endocyclic enamide. This substrate represents an interesting case, due to its unique bicyclic structure including a 1,2,4-triazine-3,6-dione subunit.

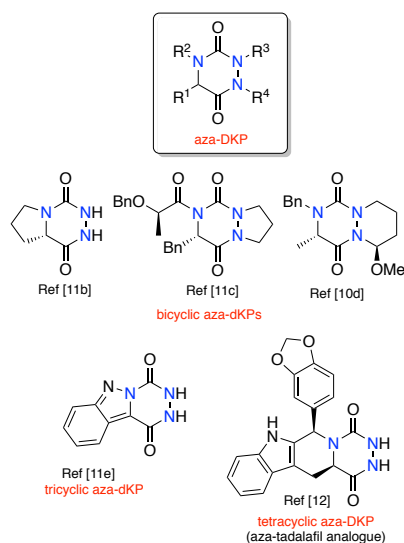


**Figure 1.** Endocyclic enamide-type substrates in Povarov reaction.

## Introduction

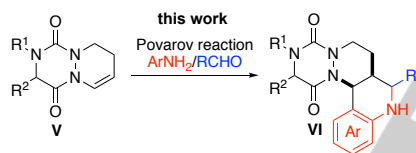
Discovered by Povarov in the 1960s,<sup>[1]</sup> the Povarov reaction was widely developed and represents nowadays a powerful tool in heterocyclic synthesis. Several reviews have been devoted to its applications in synthetic<sup>[2]</sup> or medicinal chemistry.<sup>[3]</sup> The Povarov reaction has been successfully used in diversity-oriented synthesis, as well as in target-oriented synthesis, to access tetrahydroquinolines (THQs),<sup>[4]</sup> which represent a valuable class of heterocyclic compounds. There are two currently available versions of the Povarov reaction: the two-component reaction (2CR) that involves an electron-rich olefin and an N-aryl imine, and the three-component reaction (3CR) that consists in reacting directly the olefin, the N-aryl amine, and the aldehyde. A literature survey revealed that among the different electron-rich olefins, endocyclic enamides have been sparsely reported as partners in

Aza-diketopiperazines are aza analogues of the well-known 2,5-diketopiperazines (DKPs)<sup>[9]</sup> and have been reported as an emerging scaffold with potential application in medicinal chemistry. They have been the subject of several studies in our laboratory<sup>[10]</sup> and showed promising drug-likeness properties.<sup>10a-c</sup> Most of reported in the literature aza-DKPs are monocyclic, however some fused bicyclic and tricyclic aza-DKPs (Figure 2) were obtained either from cyclic precursors (such as cyclic amino acids or hydrazine derivatives)<sup>[11]</sup> or from a monocyclic aza-DKP by post-synthetic transformation.<sup>10c,d</sup> To our knowledge, only one example of fused tetracyclic aza-DKP (Figure 2) was reported so far, an aza-analogue of tadalafil PDE5 inhibitor.<sup>[12]</sup>



**Figure 2.** General structure of an aza-DKP and selected examples of polycyclic derivatives.

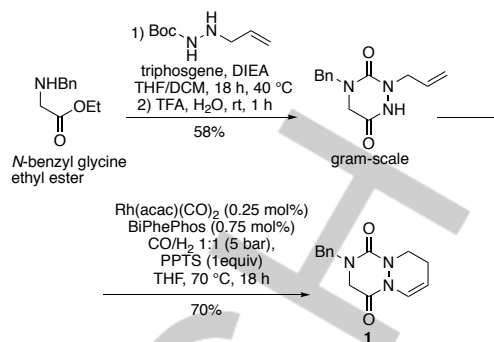
In this context, the Povarov reaction appeared as an interesting and versatile strategy to access a new family of fused tetracyclic aza-DKPs using endocyclic enamides **V** as olefin partners. The obtained tetracyclic *N*-heterocycles **VI** will combine in their structure two interesting scaffolds of interest in medicinal chemistry, a tetrahydroquinoline and an aza-diketopiperazine (Scheme 1).



**Scheme 1.** Aza-DKPs as partners in Povarov reaction.

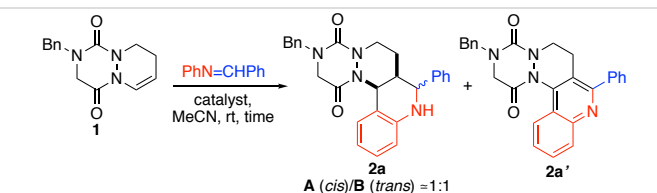
## Results and Discussion

We first synthesized the bicyclic aza-DKP precursor **1** as a simple and achiral endocyclic enamide substrate. In a first step, *N*-benzyl glycine ethyl ester reacted with *N*-allyl *tert*-butylcarbazate and triphosgene to furnish in 58% yield the desired allyl-aza-DKP. The latter was then placed under rhodium-catalyzed cyclohydrocarbonylation conditions to afford product **1** (Scheme 2). The transformation was first performed with 2 mol% of Rh-source and 6 mol% of BiPhePhos ligand and product **1** was isolated in 74% yield. As both the Rh-source and the ligand are expensive, we attempted to decrease the catalytic charge, while trying to perform the reaction on gram-scale. Finally, we succeeded in decreasing the amount of Rh-catalyst down to 0.25 mol% when performing the reaction on a 1.4 grams scale, while maintaining a good 70% yield in **1**.



**Scheme 2.** Synthesis of endocyclic aza-DKP enamide **1**

As a first assay, the reactivity of enamide **1** toward *N*-benzylideneaniline was tested in commonly used two-component Povarov reaction (2CR) conditions, with an excess of imine (1.4 equiv), in the presence of 1 equiv of  $\text{BF}_3 \cdot \text{Et}_2\text{O}$  as Lewis acid to promote the reaction, in acetonitrile, at room temperature (Table 1, entry 1). Reaction completion was total after 18 h and the expected product **2a** was obtained as a mixture of two diastereoisomers **2aA** and **2aB** in an approximative 1:1 ratio (determined by HPLC on the crude mixture), together with a little amount of the side-product **2a'** resulting from the dehydrogenative aromatization of **2a**. We were able to separate the diastereomers by reversed-phase chromatography and unambiguously assign by NMR NOESY-2D experiments the *cis*-configuration to **2aA** and the *trans*-configuration to **2aB** (see SI: for **2aA** correlation spots between the three protons of the contiguous CH of the tetrahydroquinoline system and for **2aB** correlation spots only between the two vicinal CH protons of the hexahydropyridazine heterocycle). The formation of **2a'** was probably due to the excess of the imine, which plays the role of oxidant and is reduced to the corresponding *N*-benzylaniline.<sup>[13]</sup> The total isolated yield was 45% and the two diastereomers were separated using reversed-phase chromatography. This purification technique was crucial for an optimal yield and separation (see experimental section), as the use of normal-phase chromatography or crystallization led to partial degradation and dramatically decreased the yield. Simple replacement of acetonitrile by dichloromethane led to an incomplete conversion after 18 h and more of the undesired product **2a'** was formed (Table 1, entry 2). Performing the reaction at 50 °C afforded again more side-product **2a'** (Table 1, entry 3). By reducing the amount of imine to 1 equiv in the conditions of the first experiment, the formation of **2a'** was suppressed and a higher yield of 69% was obtained (Table 1, entry 4). On the other hand, reducing the amount of the  $\text{BF}_3$  catalyst to 0.3 equiv, led to a slower process and the reaction time had to be extended to 2 days for a total conversion, while the yield dropped to 39% (Table 1, entry 5). Other Lewis acids such as  $\text{Sc}(\text{OTf})_3$ ,  $\text{Yb}(\text{OTf})_3$ , and  $\text{Dy}(\text{OTf})_3$ , which are known to be efficient in some Povarov reactions, were tested using a 30 mol% catalytic charge.<sup>2b</sup> Although the yields were similar to those obtained with  $\text{BF}_3 \cdot \text{Et}_2\text{O}$ , the reaction time had to be extended to 3-4 days for a total completion (Table 1, entries 6 to 8). Finally, the trifluoroacetic acid (TFA) and the diphenyl phosphate were also envisaged as Brønsted acids catalysts, leading respectively to 41% yield of **2a**, or to recovering the starting material (Table 1, entries 9 and 10).

**Table 1.** Optimization of the Povarov reaction of enamide **1** with benzylideneaniline

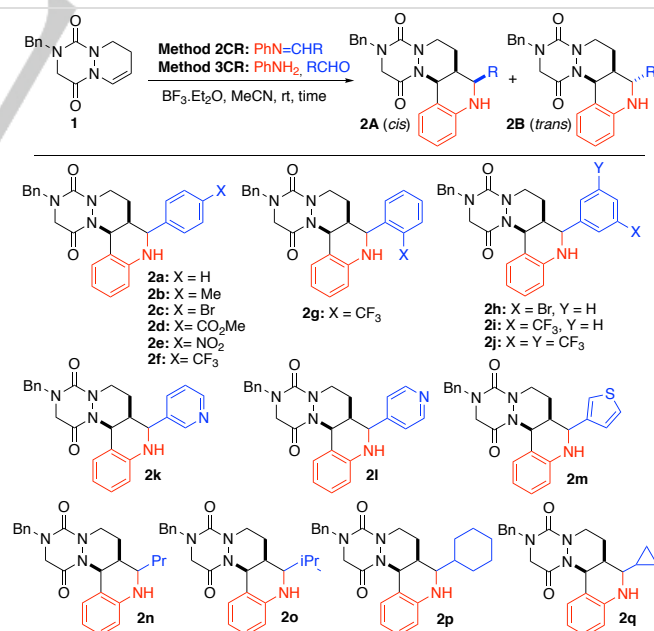
Entry	Catalyst	Ratio 1/imine/cat.	Time	Ratio <sup>[a]</sup> 1/2a/2a'	Yield (%) <sup>[b]</sup>
1	BF <sub>3</sub> .Et <sub>2</sub> O	1/1.4/1	18 h	0/9/1	45
2 <sup>[c]</sup>	BF <sub>3</sub> .Et <sub>2</sub> O	1/1.4/1	18 h	1/1/1	nd <sup>[d]</sup>
3 <sup>[e]</sup>	BF <sub>3</sub> .Et <sub>2</sub> O	1/1.4/1	18 h	0/3/2	nd
4	BF <sub>3</sub> .Et <sub>2</sub> O	1/1/1	18 h	0/1/0	69
5	BF <sub>3</sub> .Et <sub>2</sub> O	1/1/0.3	2 d	0/1/0	39
6	Sc(OTf) <sub>3</sub>	1/1/0.3	4 d	0/1/0	60
7	Yb(OTf) <sub>3</sub>	1/1/0.3	3 d	0/1/0	64
8	Dy(OTf) <sub>3</sub>	1/1/0.3	3 d	0/1/0	65
9	TFA	1/1/1	3 d	0/1/0	41
10	(PhO) <sub>2</sub> PO <sub>2</sub> H	1/1/0.3	2 d	1/0/0	nd

[a] Measured by HPLC on crude mixture. [b] Total isolated yield of **2a** (A + B). [c] DCM used as solvent. [d] Not determined. [e] Reaction performed at 50 °C.

The optimized conditions for this 2CR version for the synthesis of **2a**, were then transposed in a 3CR version, by reacting enamide **1** with aniline and benzaldehyde (Table 2, entries 1 and 2). This time, an excess of BF<sub>3</sub>.Et<sub>2</sub>O (1.5 equiv) was necessary to reach reaction completion and a slightly lower yield was obtained (59% vs 69%). The A/B ratio remained the same (≈1:1) in both cases. Having fixed the reaction conditions for the two versions (2CR and 3CR), we next investigated the scope and limitation of the Povarov reaction of enamide **1** varying first the aldehyde component (Table 2). As in the previous case, the 2CR version proved more efficient. The imines were prepared from aniline and different aromatic aldehydes.<sup>[14]</sup> The influence of the electronic nature and position of the substituents on the aromatic ring has been examined. Electron-rich systems bearing a methyl or a bromo substituent in *para* position led to a drastic loss of reactivity and the desired cycloadducts were not detected (Table 2, entries 3 and 4). In contrast, the reaction with 3-bromobenzaldehyde proved efficient in the three-component reaction conditions, with a complete conversion after 7 hours. The expected product **2h** was obtained in a 40:60 A/B ratio and in a moderate yield of 41% (Table 2, entry 10). In all cases, the presence of an electron withdrawing group (i.e. CO<sub>2</sub>Me, NO<sub>2</sub>, CF<sub>3</sub>), whatever their position on the aromatic ring, led to faster reactions. Isolated yields were around 60% with diastereomeric ratios remaining close to 1:1 (Table 2, entries 5, 6, 8, 9, and 11). Expectedly, the fastest reactions occurred with the imines derived from 4-nitrobenzaldehyde and from 3,5-bis(trifluoromethyl)benzaldehyde, as only 2 hours were needed to reach completion. Adducts **2e** and **2j** were isolated in 61% and 74% yield, respectively (Table 2, entries 6 and 12). Here again, performing the reaction in the three-component version led to a slightly lower yield (Table 2, entry 7).

Heteroaromatic aldehydes can also be involved as partners in the 3CR version of the cycloaddition. Reactions of 3- and 4-pyridyl aldehydes required the use of a larger 2.5 equiv of catalyst, as 1 equiv is coordinated to the pyridine nitrogen, and led to the expected products **2k** and **2l**, in 50% and 47% yield, respectively (Table 2, entries 13 and 14). The A/B ratios were similar in these two cases, around 70:30. The reaction with 4-pyridyl aldehyde proved much faster than the one with the 3-pyridyl derivative (3 vs 48 hours), as expected from electronic properties. In the case of 3-thiophenecarboxaldehyde the reaction led to the formation of a complex mixture and the desired product **2m** was not detected (Table 2, entry 15). It is to notice that despite the low stereoselectivity of the reaction, we were able however to isolate each diastereomer by reversed-phase chromatography in all cases except for **2g**. The set of results obtained is consistent with the putative inverse electron-demand aza-Diels-Alder nature of the Povarov reaction, showing a better reactivity of the enamide electron-rich partner **1** towards electron-depleted iminodienes.

We then envisaged to extend the scope of the reaction to aliphatic aldehydes. Owing to the instability of the corresponding imines, we turned again to the 3CR version. No reaction took place in the presence of butyraldehyde (Table 2, entry 16), while isobutyraldehyde and cyclic derivatives such as cyclohexyl and cyclopropyl aldehydes afforded the desired corresponding products (Table 2, entries 17-19). Gratifyingly, higher stereoselectivities were observed in these cases (ratios ranging from 72:28 to 99:1), and the major **A** stereoisomer (*cis*) was isolated in moderate to high yields (47 to 90% yield). The *cis* configuration was assigned by NOESY NMR experiments for compounds **2o** and **2p** (see SI).

**Table 2.** Scope and limitation of the Povarov reaction of enamide **1**: aldehyde variation

Entry	Product	Method <sup>[a]</sup>	Time (h)	Ratio <sup>[b]</sup> A/B	Yield (%) (A: B) <sup>[c]</sup>
1	<b>2a</b>	2CR	18	48:52	69 (29; 40)
2	<b>2a</b>	3CR	18	44:56	59 (23; 36)

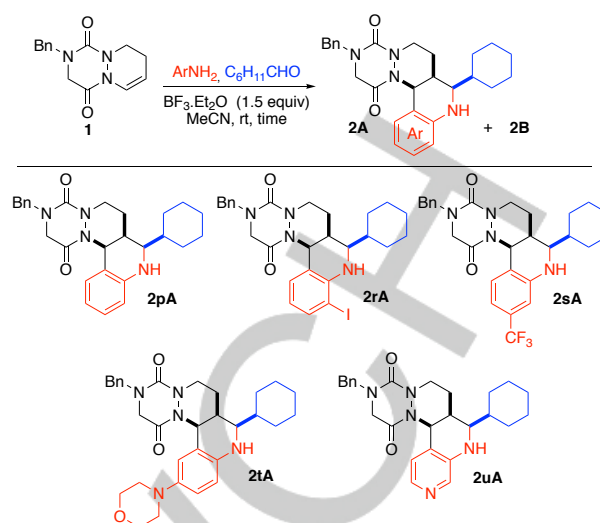
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3	<b>2b</b>	2CR	48	-	nd <sup>[e]</sup>
4	<b>2c</b>	3CR	24	-	nd <sup>[e]</sup>
5	<b>2d</b>	2CR	6	50:50	63 (24; 39)
6	<b>2e</b>	2CR	2	49:51	61 (26; 35)
7	<b>2e</b>	3CR	3	53:47	38 (13; 25)
8	<b>2f</b>	2CR	4	57:43	66 (35; 31)
9	<b>2g</b>	2CR	4	50:50	75 <sup>[f]</sup>
10	<b>2h</b>	3CR	7	40:60	41 (11; 30)
11	<b>2i</b>	2CR	7	47:53	60 (24; 36)
12	<b>2j</b>	2CR	2	42:58	74 (32; 42)
13 <sup>[d]</sup>	<b>2k</b>	3CR	48	75:25	50 (37; 13)
14 <sup>[d]</sup>	<b>2l</b>	3CR	3	71:29	47 (37; 10)
15	<b>2m</b>	3CR	24	67:33	nd <sup>[e]</sup>
16	<b>2n</b>	3CR	96	-	0
17	<b>2o</b>	3CR	48	99:1	70 (70; 0)
18	<b>2p</b>	3CR	28	90:10	90 (90; 0)
19	<b>2q</b>	3CR	96	72:28	47 (47; 0)

[a] 2CR: ratio 1/imine/BF<sub>3</sub> 1/1/1; 3CR: ratio 1/aniline/aldehyde/BF<sub>3</sub> 1/1/1/1.5. [b] Determined by HPLC at the reaction completion. [c] Total isolated yield; in brackets isolated yields of **A** and **B**. [d] 2.5 equiv of BF<sub>3</sub> used. [e] not determined. [f] Inseparable mixture of **A** and **B**.

The scope of the reaction in regard to the variation of the aryl amine partner was next investigated in the presence of the cyclohexyl aldehyde (Table 3). Three commercially available anilines functionalized in different positions have been envisaged: the 3-(trifluoromethyl)aniline, the 2-iodoaniline, and the 4-morpholinoaniline. The reactions proceeded smoothly and led to the expected cycloadducts with higher diastereoselectivities than in aromatic series, the major **A**-isomer being isolated in all cases in good yields (Table 3, entries 2-4). It is to notice that product **2sA** is the regioisomer resulting from the cyclization on the 6-position of the 3-(trifluoromethyl)aniline. Formation of the other regioisomer, cyclized on the 2-position, was not observed. 3-Aminopyridine was finally used as an *N*-heteroaryl amine partner, requiring here again 2.5 equiv of BF<sub>3</sub>.Et<sub>2</sub>O. It led to the desired product **2u**, as a unique regioisomer. It was, however, isolated in a disappointing 18% yield (**A**-isomer) from a 86:14 mixture of **A/B** diastereomers (Table 3, entry 5).

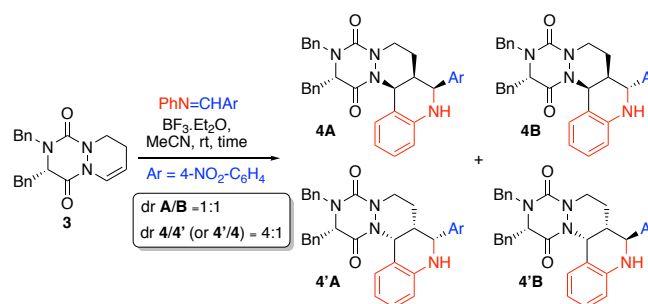
**Table 3.** Scope and limitation of the Povarov reaction of enamide **1**: arylamine variation.



Entry	Product	Time (h)	Ratio <sup>[a]</sup> A/B	Yield (%) <sup>[b]</sup>
1	<b>2p</b>	28	90:10	90
2	<b>2r</b>	5	89:11	62
3	<b>2s</b>	7	85:15	56
4	<b>2t</b>	10	94:6	86
5 <sup>[c]</sup>	<b>2u</b>	24	86:14	18

[a] Determined by HPLC at the reaction completion. [b] Isolated yield for the major product **2A**; **2B** not isolated. [c] 2.5 equiv of BF<sub>3</sub> used.

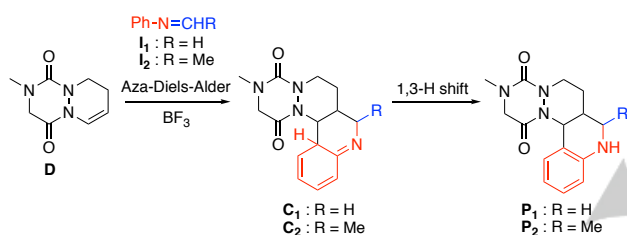
Finally, in order to study an asymmetric version of the reaction, we prepared the enantiopure endocyclic enamide **3** using L-phenylalanine.<sup>12a</sup> The reaction was first attempted with aniline and isobutyraldehyde (3CR) but no product was formed after 24 h. We then turned to the more reactive (4-nitrophenyl)-*N*-phenylmethanimine and this time the reaction with **3** proved efficient and led, after 7 h, to the expected cycloadduct, formed as a mixture of four stereoisomers, and isolated in 21% yield (Scheme 3). The ratio **A/B** was 1:1 (like in the case of **2e**) and a diastereomeric ratio of 4:1 resulted from the chiral induction for each stereoisomer **A** and **B**. Despite our efforts, only one of the major stereoisomers could be isolated. The analysis by NMR spectrometry (NOESY experiment) indicated that it corresponded to a stereoisomer **B** (*trans*). Discrimination between **4B** and **4'B** was unfortunately impossible at this stage in the absence of an X-ray crystallographic structure.



**Scheme 3.** Asymmetric version: use of enantiopure enamide **3**.

## Theoretical study

In order to get a better insight into the mechanistic details of these reactions, we examined the course of this Povarov reaction by computational means. DFT calculations were performed at the M062X/6-31+G(d,p) level of theory, which proved appropriate for many organic transformations and has been shown to provide accurate energies for cycloaddition reactions.<sup>[15],[16]</sup> Solvation by acetonitrile was taken into account by using a solvation model based on density (SMD) (for the computational details and benchmark of the method, see SI). The Povarov reaction has been studied computationally in a few cases, involving different dienophiles, most of the time simpler monosubstituted ones.<sup>[17-21]</sup> The cycloaddition part of the process was also shown to preferably proceed through involvement of the iminium aza-diene, in a two-step mechanism. The final 1,3-hydrogen shift leading to a highly favorable rearomatization was reported to be an easy step. We thus considered only the cycloaddition step of the Povarov reaction in our study. Calculations were first envisaged with the electron-rich N-methyl dienophile **D**, considered as a good model of the N-benzyl substrate **1** used in the experimental part, and the unsubstituted electron-poor aza-diene **I** (Scheme 4).



**Scheme 4.** Povarov reaction of dienophile **D** and N-phenyl imines **I**

First the processes involving the uncomplexed imine **I** and its complexed **BF<sub>3</sub>-I** iminium form were compared. Noteworthy, the optimized aza-diene conformation displayed a slightly bent C=N-C=C dihedral angle of 44° for **I**. A similar 41° distortion was observed for the complexed iminium derivative **BF<sub>3</sub>-I**. Evaluation of the frontier orbitals energies confirmed the preferential interaction between the HOMO of the dienophile **D** with the LUMO of the aza-diene **I** or **BF<sub>3</sub>-I**, and thus the inverse electron demand character of the cycloaddition process. The energy difference between the reacting molecular orbitals (dienophile HOMO and diene LUMO) was lower when taking the complexed **BF<sub>3</sub>-I** diene (6.2 eV vs 7 eV for **I**), a preliminary data suggesting a more favorable Lewis acid assisted cycloaddition. In each case, the LUMO coefficients proved bigger on the terminal N=CH<sub>2</sub> part of the aza-diene. Quantitative evaluation of the preferred pathway on the activation energy was then undertaken, by localization of the transition states (TS) of the cycloaddition. Two orientations, corresponding to the *endo/exo* approaches were considered (Table 4). The computed reaction profiles proved different. Indeed, the imine derivative **I** displayed an asynchronous concerted mechanism (1.7 vs 2.7-2.8 Å, in the TS, for the CH-CH<sub>2</sub> and CH-CHAr bonds, respectively). In contrast, a two-steps cycloaddition process was computed in the presence of the **BF<sub>3</sub>-I** iminium, with the formation of an intermediate zwitterion **ZI<sub>1</sub>**, before cyclization involving a Friedel-Crafts type reaction. The first step was the rate determining one, since the energy difference between TS<sub>b</sub> and **ZI<sub>1</sub>** was lower than the one between TS<sub>a</sub> and the substrates. Even if

non determining, the Friedel-Crafts type cyclization proved much easier in the case of an *endo* approach ( $\Delta G^\ddagger = 2.8$  kcal.mol<sup>-1</sup> vs 13.5 for the *exo* approach). Comparing the activation energies of the rate determining step in the uncomplexed/complexed case (compare entries 1-2 with 3-4) showed that with a much higher energy was required when the imine uncomplexed aza-diene was involved ( $\Delta\Delta G^\ddagger = 16.5$  kcal.mol<sup>-1</sup>). The Lewis-acid catalyzed cycloaddition is thus, expectedly, the most favored process.

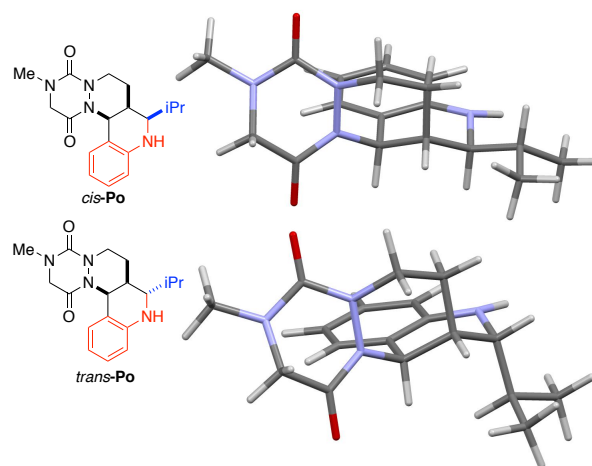
We next considered the involvement of a substituted iminium aza-diene **BF<sub>3</sub>-I<sub>2</sub>**, bearing a methyl group, as a model of the alkyl derivatives used experimentally. Here again, the dienic moiety of the optimized structure was not planar (dihedral angle of 56° for the *E* isomer) and this raised the problem of the *E/Z* geometry of the iminium. The optimized *E* isomer indeed proved less stable than the *Z* isomer, even if the energy difference remained small ( $\Delta\Delta G = 0.7$  kcal.mol<sup>-1</sup>). The *Z* isomer displayed an even larger dienic CCNC dihedral angle of 81°, meaning *quasi* perpendicular methyl and phenyl groups. Four approaches were next envisaged for the cycloaddition (*E/Z* geometries and *endo/exo* approaches, Table 4, entries 5-8). Here again, two-steps transformations were computed, with the formation of a zwitterionic intermediate adduct **ZI<sub>2</sub>**, and a subsequent Friedel-Crafts cyclization. The first addition step of this formal cycloaddition process was, here again, the rate determining one. The process required higher activation energies than in the unsubstituted case, because of the larger steric hindrance in this case. The *endo* approaches were slightly preferred to the *exo* ones ( $\Delta\Delta G^\ddagger = 1.9$  kcal.mol<sup>-1</sup>, compare entries 5 and 6). Even if the *E*-iminium is less stable, the TS involving this geometry proved slightly more favorable ( $\Delta\Delta G^\ddagger = 0.8$  kcal.mol<sup>-1</sup> for the most favored *endo* approach, compare entries 5 and 7). This is probably due to the more unfavorable steric effects with the *Z* isomer. The most favored approach was thus the *E-endo* one, that would lead to the formation of the *cis-P2* cycloadduct, as experimentally observed. However, the activation energy differences remained relatively small in this case, involving a methyl substituent. It is probable that the *i*Pr or Cy substituent used experimentally would induce greater differences between the *E* and *Z* approaches and this explains the higher diastereoselectivity observed in these cases. The endergonicity of these cycloadditions is the reflect of a dearomatization process that is not thermodynamically favored. The re-aromatization occurring next, through the 1,3-hydrogen shift, is most probably the driving force of the process, and shifts the process toward the formation of the re-aromatized cycloadduct **P2**, that is, experimentally, the only type of product isolated. The *cis-P2* cycloadduct proved computationally to be slightly more stable than the *trans-P2* one, by 0.18 kcal.mol<sup>-1</sup>, in line with the experimental data, which showed the preferred formation of the *cis* isomer in the aliphatic aldehyde series.

**Table 4.** DFT calculations for the cycloaddition of enamide **D** with imine/iminium derivatives **I**/**BF<sub>3</sub>-I**.

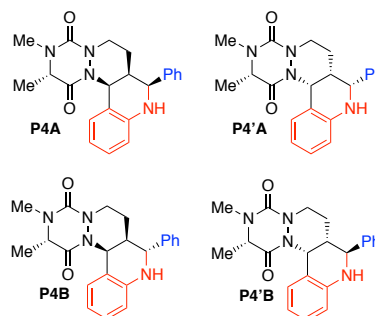
Entry	R	X	Approach	$\Delta G^\ddagger$ TS <sub>a</sub> [a]	$\Delta G_r$ ZI[a,b]	$\Delta G^\ddagger$ TS <sub>b</sub> [a,c]	$\Delta G_r$ C[a,d]
1	H	-	endo	36.8	-	-	5.6
2	H	-	exo	38.1	-	-	5.0
3	H	BF <sub>3</sub>	endo	20.8	13.3	16.0	-1.8
4	H	BF <sub>3</sub>	exo	20.3	13.8	27.3	-1.6
5	Me	BF <sub>3</sub>	E-endo	29.7	23.6	26.2	11.2
6	Me	BF <sub>3</sub>	E-exo	31.6	22.8	34.3	4.8
7	Me	BF <sub>3</sub>	Z-endo	30.5	23.2	26.4	6.5
8	Me	BF <sub>3</sub>	Z-exo	32.6	28.9	37.4	13.8

[a] Gibbs Free Energy differences relative to the separated substrates, in kcal.mol<sup>-1</sup>. [b] zwitterionic adduct ZI. [c] TSb transition state for the second step. [d] cycloadduct C.

In order to get more insight on the high *cis*-diastereoselectivity observed with aliphatic aldehydes, we also examined, computationally, the 3D-structures of *cis*-**Po** and *trans*-**Po** analogues of compounds **2o** in which the N-Bn was replaced by an N-Me (Figure 3). Interestingly, the calculation showed, here again, that the *cis*-isomer is slightly more stable than the *trans*-isomer by 0.35 kcal/mol. Even if the difference remains small, this lower energy for the *cis*-isomer is in line with the experimental data and can be understood considering the isopropyl substituent, which occupies a *pseudo*-equatorial position in *cis*-**Po** and a *pseudo*-axial position in *trans*-**Po** (see SI for details).

**Figure 3.** Computed conformations for *cis* and *trans* **Po**.

The conformations of the analogues **P4** of structures **4** in which the two Bn groups were replaced by Me groups and the 4-NO<sub>2</sub>-C<sub>6</sub>H<sub>4</sub> by a Ph group (Figure 4), were also optimized (see in SI the four corresponding stereoisomers). The Me-substituent on the stereogenic carbon was found in pseudo-equatorial position in the four cases, while the Ph-substituent occupied a pseudo-equatorial position in **P4'A** and **P4'B**, and a pseudo-axial position in **P4A** and **P4'B**. The analysis of some computed distances in **P4B** and **P4'B**, of around 4 Å (see in SI), could explain why some expected dipolar couplings were not observed by NMR NOESY-experiment on product **4B** or **4'B**, and thus the difficulties encountered in the assignment of the relative configuration of the isolated stereoisomer.

**Figure 4.** Structures **P4** used for the calculations (see in SI).

## Conclusion

In summary, we succeeded in the application of the Povarov reaction to endocyclic enamides based on a bicyclic azadiketopiperazine (aza-DKP) structure as original dienophiles partners. The cycloaddition tolerated various aldehydes and anilines and has been performed in the presence of BF<sub>3</sub> as the Lewis acid catalyst, either as a two-component or a three-component reaction (2CR or 3CR), depending on the nature of the aldehyde partner. With aromatic aldehydes the reaction showed a low *cis/trans* selectivity, but the two diastereomers could be separated by column chromatography. On the other

hand, with aliphatic aldehydes the reaction was highly *cis*-diastereoselective. The method represents an efficient strategy for the structural diversification of the aza-DKP scaffold. It allowed the synthesis of a new family of molecules combining in a fused tetracyclic N-heterocyclic structure two interesting scaffolds for medicinal chemistry, a tetrahydroquinoline and a bicyclic azadiketopiperazine. Mechanistic details of the cycloadditions have been examined by computational means. This confirmed the role of the catalyst in lowering the energy barriers and showed that the cycloaddition was a stepwise process. Even if small energy differences were observed between the approaches considered in the presence of methyl substituted iminium, the conclusions were in full agreement with the experimental results.

## Experimental Section

**General information.** Reagents were obtained from commercial sources and used without any further purification. Thin layer chromatography was performed on silica gel 60 F254 plates.

NMR spectra were recorded at 400 or 500 MHz for  $^1\text{H}$  and at 100 or 125 MHz for  $^{13}\text{C}$ . Chemical shifts are reported in parts per million (ppm) relative to residual solvent and coupling constants ( $J$ ) are reported in hertz (Hz).  $\text{CDCl}_3$  was filtered previously on basic alumina. Assignments of  $^1\text{H}$  and  $^{13}\text{C}$  signals were made by DEPT, COSY, HSQC, HMBC, NOESY-2D experiments for compounds **2aA**, **2aB**, **2oA**, **2pA**, **4B** (or **4'B**). HRMS were performed with quadrupole /time-of-flight (Q-TOF) analysers, using either electrospray ionization (ESI) at  $T_{\text{source}} = 340\text{ }^\circ\text{C}$ ,  $V_{\text{cap}} = 4000\text{ V}$ , or atmospheric pressure chemical ionization (APCI) at  $T_{\text{gas}} = 300\text{ }^\circ\text{C}$ ,  $T_{\text{vap}} = 380\text{ }^\circ\text{C}$ ,  $V_{\text{corona}} = 4\mu\text{A}$ . The purification on reversed-phase chromatography was performed on a Gilson PLC 2020 apparatus equipped with Interchim Flash chromatography column PF-30C18HP-F0025. The solvents used were Solvent A (0.1% TFA in MeCN, v/v) and Solvent B (0.1% TFA in H<sub>2</sub>O, v/v). The program started with a 5 min plateau at 10% of Solvent A, then a gradient for 30 minutes from 10% to 100% of Solvent A and a 5 min plateau at 100% of Solvent A.

### Synthesis of the enamide precursor 1:

**Step 1.** In a dry RBF (round-bottom flask) under argon, to a solution of triphosgene (1.05 g, 0.335 equiv) in anhydrous THF (61.9 mL), was added dropwise over 5 minutes a solution of ethyl 2-(benzylamino)acetate (2 g, 10.3 mmol) and DIEA (3.78 mL, 2.1 equiv) in anhydrous THF (13 mL) and DCM (13 mL). The mixture was stirred at room temperature for 15 min. A solution of *N*'-(prop-2-en-1-yl)(tert-butoxy)carbohydrazide (1.78 g, 1 equiv) and DIEA (1.88 mL, 1.1 equiv) in anhydrous THF (15 mL) was added dropwise and the mixture was heated at 40°C overnight. The mixture was filtered and evaporated in vacuo. A mixture TFA/water: 95/5 (13 mL) was added and the mixture was stirred at room temperature for 1 h before being evaporated. The crude mixture was purified on silica gel eluting with 70% ethyl acetate in heptane to afford the 2-allyl-4-benzyl-1,2,4-triazinane-3,6-dione as a yellowish solid (1.45 g, 57%).

**$^1\text{H}$  NMR** (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.37-7.23 (m, 5H), 5.82 (ddt,  $J = 17.2, 10.2, 6.2$  Hz, 1H), 5.32 (br d,  $J = 17.2$  Hz, 1H), 5.29 (bs d,  $J = 10.2$  Hz, 1H), 4.51 (s, 2H), 4.17 (bs d,  $J = 6.5$  Hz, 2H), 3.67 (s, 2H).  **$^{13}\text{C}$  NMR** (100 MHz,  $\text{CDCl}_3$ )  $\delta$  163.9, 154.5, 135.8, 131.3, 129.1, 128.5, 128.3, 120.7, 51.0, 50.5, 48.8.

**Step 2.** A solution of  $\text{Rh}(\text{CO})_2(\text{acac})_2$  (3.55 mg, 0.25 mol%) and Biphephos (32.5 mg, 0.75 mol%) in anhydrous THF (2 mL), prepared in a Schlenk glassware under an argon atmosphere, was introduced under argon into a stainless steel autoclave containing the 2-allyl-4-benzyl-1,2,4-triazinane-3,6-dione (1.35 g, 1 equiv) and pyridinium *p*-toluenesulfonate (1.38 g, 1 equiv) in anhydrous THF (49 mL). The reactor was purged three times with

$\text{H}_2/\text{CO}$  (1:1, 5 bars) and filled with  $\text{H}_2/\text{CO}$  (1:1, 5 bars). The reactor was heated to 70 °C and stirred for 16 h. The reactor was then cooled to ambient temperature and vented to ambient pressure. The reaction mixture was evaporated. The residue was retaken in EtOAc and washed with brine, the organic phase was then dried over  $\text{Na}_2\text{SO}_4$  and concentrated. The crude product was purified on gel silica eluting with 50% ethyl acetate in heptane to afford product **1** as a yellowish solid (1 g, 71%).

**$^1\text{H}$  NMR** (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.35-7.26 (m, 5H), 7.06 (dt,  $J = 8.4, 2.0$  Hz, 1H), 5.29 (dt,  $J = 8.4, 4.3$  Hz, 1H), 4.50 (s, 2H), 3.85 (t,  $J = 5.5$  Hz, 2H), 3.68 (s, 2H), 2.33-2.27 (m, 2H).  **$^{13}\text{C}$  NMR** (100 MHz,  $\text{CDCl}_3$ )  $\delta$  160.5, 155.0, 135.9, 129.1, 128.5, 128.2, 120.2, 107.3, 50.8, 48.8, 40.2, 22.5. **HRMS** (ESI-TOF): calcd. for  $\text{C}_{14}\text{H}_{16}\text{N}_3\text{O}_2$  [ $\text{M}+\text{H}$ ] $^+$ : 258.1243; Found: 258.1236.

### Povarov reaction

**General Procedure A (two-component reaction):** To a round bottom flask under argon was placed the imine (0.18 mmol, 1 equiv) in acetonitrile (1 mL) and  $\text{BF}_3\cdot\text{OEt}_2$  (22  $\mu\text{L}$ , 1 equiv) was added to the reaction mixture which was stirred for 5 min at room temperature. Enamide **1** (46 mg, 0.18 mmol, 1 equiv) in acetonitrile (1 mL) was then added to the solution and stirred at room temperature until completion (monitored by HPLC). The solvent was removed under vacuo and DMSO (500  $\mu\text{L}$ ) was added and the crude product **2** obtained as a mixture of two diastereoisomers **A** and **B** was purified by reversed-phase chromatography ( $\text{H}_2\text{O}/\text{MeCN} + 0.1\%$  TFA) to afford separated pure products **2A** and **2B**.

**General Procedure B (three-component reaction):** To a round bottom flask under argon was placed enamide **1** (37.4 mg, 0.15 mmol, 1 equiv) in acetonitrile (1 mL), the aldehyde (0.15 mmol, 1 equiv) and the aniline (0.15 mmol, 1 equiv) with acetonitrile (1 mL).  $\text{BF}_3\cdot\text{OEt}_2$  (28  $\mu\text{L}$ , 1.5 equiv) was then added to the reaction mixture which was stirred until completion (monitored by HPLC) at room temperature. The solvent was removed under vacuo and DMSO (500  $\mu\text{L}$ ) was added and the crude product **2** obtained as a mixture of two diastereoisomers **A** and **B** was purified by reversed-phase chromatography ( $\text{H}_2\text{O}/\text{MeCN} + 0.1\%$  TFA) to afford separated pure products **2A** and **2B**.

3-benzyl-8-phenyl-2,3,6,7,7a,8,9,13b-octahydro-[1,2,4]triazino[2',1':1,2]pyridazino[4,3-c]quinoline-1,4-dione (**2a**) was obtained according to the general procedure A, performed on a 0.18 mmol scale (53 mg, 69%) and according to the general procedure B, performed on a 0.15 mmol scale (35 mg, 69%).

**2aA:** white amorphous solid (by procedure A: 22 mg, 29%; by procedure B: 13 mg, 23%).  **$^1\text{H}$  NMR** (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  7.45-7.30 (m, 10H), 7.10 (tdd,  $J = 7.1, 1.6, 0.8$  Hz, 1H), 6.80 (dt,  $J = 7.8, 1.3$  Hz, 1H), 6.71 (ddd,  $J = 7.9, 7.3, 1.2$  Hz, 1H), 6.62 (dd,  $J = 8.0, 1.1$  Hz, 1H), 6.16 (d,  $J = 5.1$  Hz, 1H,  $\text{NCH}_2\text{CH}$ ), 4.84 (d,  $J = 2.5$  Hz, 1H,  $\text{CHPh}$ ), 4.75 (d,  $J = 14.7$  Hz, 1H,  $\text{NCH}_2\text{Ph}$ ), 4.35 (ddd,  $J = 12.5, 4.9, 2.4$  Hz, 1H,  $\text{NCH}_2\text{CH}_2$ ), 4.22 (d,  $J = 14.7$  Hz, 1H,  $\text{NCH}_2\text{Ph}$ ), 3.90 (d,  $J = 15.8$  Hz, 1H), 3.82 (d,  $J = 15.8$  Hz, 1H), 2.92 (td,  $J = 12.7, 3.0$  Hz, 1H,  $\text{NCH}_2\text{CH}_2$ ), 2.17 (dddd,  $J = 11.9, 5.1, 3.8, 2.6$  Hz, 1H,  $\text{CHCH}_2$ ), 1.92 (qd,  $J = 13.0, 4.9$  Hz, 1H), 1.37 (dd,  $J = 13.6, 3.1$  Hz, 1H).  **$^{13}\text{C}$  NMR** (101 MHz,  $\text{CDCl}_3$ ):  $\delta$  163.8 (C=O), 155.8 (C=O), 144.6 (C<sub>q</sub>), 140.3 (C<sub>q</sub>), 136.0 (C<sub>q</sub>), 128.9 (C<sub>Ar</sub>), 128.73 (C<sub>Ar</sub>), 128.68 (C<sub>Ar</sub>), 128.5 (C<sub>Ar</sub>), 128.07 (C<sub>Ar</sub>), 128.02 (C<sub>Ar</sub>), 126.8 (C<sub>Ar</sub>), 126.5 (C<sub>Ar</sub>), 118.7 (C<sub>Ar</sub>), 116.1 (C<sub>q</sub>), 115.0 (C<sub>Ar</sub>), 58.8 (CH), 52.2 (CH), 50.4 (CH<sub>2</sub>), 48.3 (CH<sub>2</sub>), 45.0 (CH<sub>2</sub>), 37.7 (CH), 19.2 (CH<sub>2</sub>). **HRMS** (ESI-TOF): Calculated for  $\text{C}_{27}\text{H}_{27}\text{N}_4\text{O}_2$  [ $\text{M}+\text{H}$ ] $^+$ : 439.2134; Found: 439.2124.

**2aB:** white amorphous solid (by procedure A: 31 mg, 40%; by procedure B: 22 mg, 36%).  **$^1\text{H}$  NMR** (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  7.48-7.18 (m, 10H), 7.13 (dddd,  $J = 7.8, 6.8, 2.0, 0.8$  Hz, 1H), 6.72-6.62 (m, 3H), 5.99 (bs, 1H), 5.43 (d,  $J = 5.0$  Hz, 1H,  $\text{NCH}_2\text{CH}$ ), 4.73 (d,  $J = 14.7$  Hz, 1H,  $\text{NCH}_2\text{Ph}$ ), 4.52-4.40 (m, 2H), 4.25 (d,  $J = 14.7$  Hz, 1H,  $\text{NCH}_2\text{Ph}$ ), 3.87 (d,  $J = 15.7$  Hz, 1H), 3.80 (d,  $J = 15.7$  Hz, 1H), 3.16 (td,  $J = 12.7, 3.1$  Hz, 1H), 2.25 (dddd,  $J = 12.4, 5.0, 3.9, 2.3$  Hz, 1H,  $\text{CHCH}_2$ ), 2.03 (qd,  $J = 12.8, 4.7$  Hz, 1H), 1.87 (dd,  $J = 13.4, 3.3$  Hz, 1H).  **$^{13}\text{C}$  NMR** (101 MHz,  $\text{CDCl}_3$ ):  $\delta$  163.5 (C=O), 155.9









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(t,  $J = 4.7$  Hz, 1H), 4.12 – 3.93 (m, 1H), 3.50 (d,  $J = 14.8$  Hz, 1H), 3.42 (d,  $J = 2.1$  Hz, 1H), 2.73 (qd,  $J = 14.0$ , 4.6 Hz, 2H), 1.56 (ddd,  $J = 11.9$ , 5.8, 3.4 Hz, 1H), 1.51 – 1.38 (m, 2H), 0.87 (d,  $J = 9.7$  Hz, 1H).  $^{13}\text{C}$  NMR (126 MHz,  $\text{C}_6\text{D}_6$ )  $\delta$  163.7, 154.1, 150.2, 147.1, 142.7, 136.6, 135.3, 130.2, 128.9, 128.7, 128.6, 128.3, 128.0, 127.2, 126.4, 126.0, 123.6, 118.0, 114.7, 113.5, 60.2, 57.8, 48.9, 47.1, 44.4, 36.5, 36.3, 25.5. HRMS (ESI-TOF): Calculated for  $\text{C}_{34}\text{H}_{32}\text{N}_5\text{O}_4$   $[\text{M}+\text{H}]^+$ : 574.2454.; Found: 574.2440.

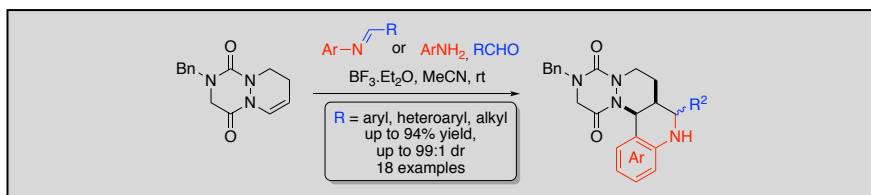
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**Keywords:** aza-diketopiperazines • Povarov reaction • enamides • N-Heterocycles • DFT study

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## Entry for the Table of Contents



An endocyclic enamide having a unique bicyclic structure including a 1,2,4-triazine-3,6-dione subunit was used as an olefin partner in the Povarov reaction. This represents an efficient strategy to access a new family of fused tetracyclic N-heterocycles which combine in their structure two scaffolds of interest in medicinal chemistry, a tetrahydroquinoline (THQ) and an aza-diketopiperazine (aza-DKP).