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Rh(II)-carbenoid mediated 2*H*-azirine ring-expansion as a convenient route to non-fused photo- and thermochromic 2*H*-1,4-oxazines

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ABSTRACT

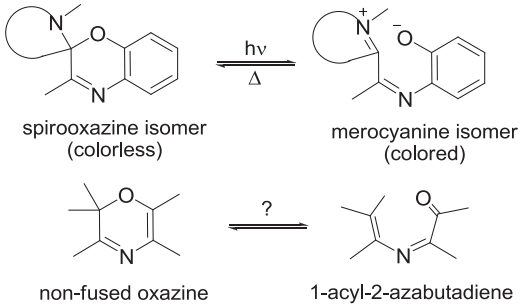
The $Rh_2(OAc)_4$-catalyzed domino reaction of 2*H*-azirines with 2-acyl-2-diazoacetates provides a unique synthetic approach to non-fused 2*H*-1,4-oxazines. The reaction proceeds via sequential formation of a rhodium carbenoid, an azirinium ylide, and a 1-acyl-1-(alkoxycarbonyl)-2-azabuta-1,3-diene to give, after 1,6-π-electrocyclization, a 2*H*-1,4-oxazine derivative in good yield. The observed stereoselectivity of 2-azadiene formation is consistent with DFT calculations of the azirinium ylide–2-azadiene isomerization, providing evidence for the ylide mechanism of the reaction. The substitution pattern and configuration of the carbon–carbon double bond in 2-azadienes has a dramatic influence on their cyclization to oxazines: the CO_2R group on C^4 stabilizes an open-chain form and, as the result of this, a new class of stable 2-azadienes, 1-acyl-2-azadiene-1,4-dicarboxylates, could be isolated. The 1,4-oxazines obtained by this method are the first representatives of monocyclic 2*H*-1,4-oxazine derivatives, which exhibit photo- and thermochromic activity.

1. Introduction

Photochromism is a phenomenon involving a photoinduced reversible transformation between two molecular states whose absorption spectra are significantly different. Organic photochromic compounds have been the subject of intense investigations as to their potential applications. These include erasable optical disks,[1] lenses,[2] light filters and photo-switching devices,[3] three-dimensional memory,[4] photochromic liquid crystals,[3] photochromic plastics,[4] and photoswitchable biomaterials.[5]

One of the promising classes of organic photochromic materials having excellent fatigue resistance are spirooxazines.[6] These molecules contain a fused ring-substituted 2*H*-1,4-oxazine moiety in which the C^2 atom is involved in a spiro linkage. Under UV irradiation these colorless compounds undergo oxazine ring opening by C–N bond cleavage to give the colored merocyanine open-chain isomer, which cyclizes back to the oxazine in the dark. In the case of non-fused 2*H*-1,4-oxazines the open-chained valence isomer would be 1-acyl-2-azabuta-1,3-diene (Scheme 1).

The structural diversity of the known 2*H*-1,4-oxazines is limited to *ortho*-fused derivatives because of their synthetic availability:



Scheme 1. Valence isomerism of spiro benzoxazines and non-fused oxazines.

a few simple and efficient methods for the preparation of *ortho*-fused spirooxazines from *o*-hydroxynitroso compounds, 1-amino-2-naphthols and several other compounds have been elaborated.[6a,c] A few examples of the preparation of photochromic non-spiro *ortho*-fused 2*H*-1,4-oxazines are also known.[7] To date, there are no general methods of preparation of non-fused 2*H*-1,4-oxazines. Attempts to synthesize them by standard protocols have failed.[8] 6-Alkoxy- or 6-acetoxy-2*H*-1,4-oxazines were isolated as byproducts of alkylation or acylation of the corresponding oxazinones.[9] 3,5-Diphenyl-2*H*-1,4-oxazine, which was synthesized

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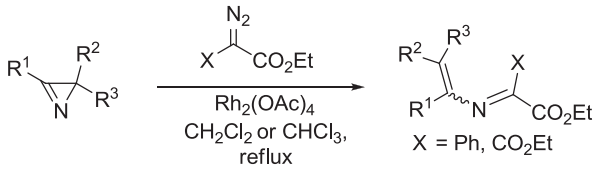
from diphenacyl ether and ammonia is the only stable non-fused 1,4-oxazine prepared in reasonable yield.[10] Meanwhile, it is known that aryl-substituted 2*H*-azirines react with diazo esters, such as dimethyl diazomalonate and methyl 2-diazo-2-phenylacetate in the presence of rhodium catalyst to give substituted 2-azadienes in good yields (Scheme 2).[11]



Scheme 2. The reaction of azirines with diazo esters.

It is not hard to notice that when X=acyl (Scheme 2) the azadienes, which could be expected to be formed in this reaction are valence isomers of the target non-fused oxazines (see Scheme 1). The first examples of preparative synthesis of non-fused 2*H*-1,4-oxazines, using the $Rh_2(OAc)_4$-catalyzed reaction of 2-acyl-2-diazoacetates with aryl-substituted 2*H*-azirines, have already been reported in our preliminary publication.[12]

In order to determine the scope and limitations of this reaction, the examination of reactions of a wide range of substituted azirines and 2-acyl-2-diazoacetates have been carried out in the work reported herein. The influence on product yield by the reaction conditions and the method of carrying out the reactions was also investigated. Quantum chemical calculations were performed to verify the mechanism of the reaction and rationalize the influence of the structure of starting compounds on the outcome of the process. The ability of the products to display photo- and thermochromic activity was demonstrated.

2. Results and discussion

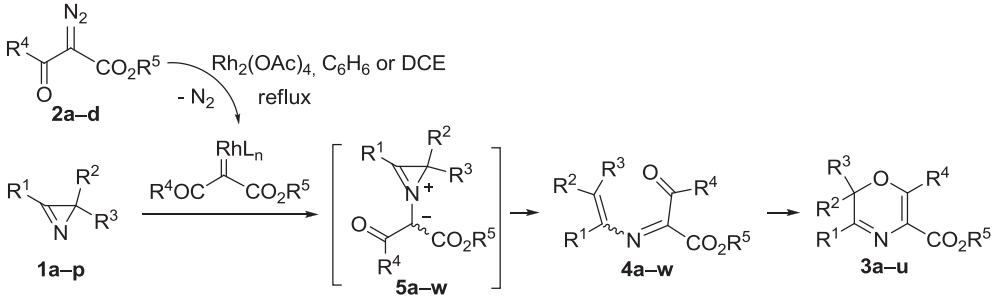
2.1. $Rh_2(OAc)_4$-catalyzed reaction of 2*H*-azirines with diazo keto esters

The common procedure for carrying out the catalytic reaction of heteroatomic compounds[13] including azirines[11] with diazo esters involves very slow addition of a solution of diazo compound to a boiling solution of nitrogen substrate and catalyst in an appropriate solvent. Such reaction conditions usually prevent the competing reaction of the intermediate Rh(II)-carbenoid with the diazo compound. For the investigation of the reactivity of rhodium carbenoids, derived from the diazo keto ester, toward azirines under these conditions we started with the $Rh_2(OAc)_4$-catalyzed test reaction of ethyl 2-diazoacetoacetate **2a** with 2,3-diphenyl-2*H*-azirine **1a**. It is known that diazo compound **2a** in benzene or fluorobenzene decomposes in the presence of $Rh_2(OAc)_4$ or Cu(hfacac)$_2$ at temperatures over 70 °C.[13a,14]

Slow addition of the solution of diazoacetoacetate **2a** to a mixture of azirine **1a** and $Rh_2(OAc)_4$ in benzene at 80 °C (method ***A***) gave rise to 2*H*-1,4-oxazine **3a**, which was isolated in 37% yield (Scheme 3, Table 1).

In this case no 2-azadiene **4a** was observed in the reaction mixture. Analogously, oxazines **3b**,**c**,**e**,**g** were synthesized in 11–45% yield from **1a**–**c** and ethyl 2-acyl-2-diazoacetates **2a**–**c** (Table 1, entries 2, 3, 5, 7).[12]

The yields of the products obtained according to the described procedure proved to be very sensitive to variation of the substituents in both the azirine and diazo compound. The nitrogen atom of some substituted azirines is expected to coordinate to the rhodium catalyst, substantially reducing its efficiency. Besides, the substituent R^4 in the rhodium carbenoid affects its reactivity not only toward azirines but also the initial diazo compound. The latter reactions result in the formation of side products, 'carbene dimers',[15] and the products of insertion to CH-bonds.[16] To achieve



Scheme 3. The reaction of azirines **1a**–**p** with 2-acyl-2-diazoacetates **2a**–**d**.

acceptable yields of oxazines for the majority of the reactions the preparation procedure needs to be modified. Experiments to optimize the procedure showed that the yields of oxazines **3a**,**e**,**g** (entries 1, 5, 7) derived from ethyl 2-diazoacetoacetate **2a** could be substantially improved by changing the solvent from benzene to 1,2-dichloroethane (DCE) as well as modifying the rate of addition of the diazo compound: three equivalents of diazo compound were added, one equivalent every 5 min (method ***B***).[12] According to the ^{1}H NMR data the reaction in 1,2-dichloroethane gave lower amounts of byproducts. The decrease in product yield over prolonged reaction time was attributed to the lability of the starting azirines and the oxazines formed under the reaction conditions. By use of this modified procedure oxazines **3a**,**e**,**g**,**i**–**p** were synthesized from 3-mono-, 2,3-di- and 2,2,3-trisubstituted azirines **1a**–**k** and diazo compound **2a** in good yields (entries 1, 5, 7, 9–16). The shortening of the reaction time is especially important for preparation of the thermally unstable oxazines, such as compound **3v**, whose half-life in boiling DCE is about 15 min.

2,2-Dimethyl-3-phenyl-2*H*-azirine **1m** failed to react with diazo compound **2a** under conditions either of procedure ***A*** or procedure ***B***. However, when during the addition of the diazo compound additional portions of $Rh_2(OAc)_4$ were introduced into the reaction mixture (method ***C***), the corresponding oxazine **3t** was obtained in 43% yield (entry 21).

According to TLC- and ^{1}H NMR-analysis two products (oxazines **3** and 2-azadienes **4**) were formed in the reactions of 2,2-disubstituted and 2,2,3-trisubstituted azirines **1a**,**h**–**j**,**l**,**n**,**o** (entries 1, 13–15, 17–18, 22–24) when carried out using a fast addition

Table 1
$Rh_2(OAc)_4$-catalyzed reaction of azirines **1a**–**p** with diazo compounds **2a**–**d**

Entry	Azirine **1**	R^1	R^2	R^3	Diazo ester **2**	R^4	R^5	Isolated yields of oxazines **3** and azadienes **4** by method ***B*** (by method ***A***), %
1	**1a**	Ph	Ph	H	**2a**	Me	Et	75 (37) **3a**
2	**1a**	Ph	Ph	H	**2b**	Ph	Et	39 (45) **3b**
3	**1a**	Ph	Ph	H	**2c**	CF_3	Et	(83)[a] **3c**
4	**1a**	Ph	Ph	H	**2d**	4-NCC_6H_4	Me	79 **3d**
5	**1b**	Ph	H	H	**2a**	Me	Et	73 (11) **3e**
6	**1b**	Ph	H	H	**2c**	CF_3	Et	(62)[a] **3f**
7	**1c**	4-MeC_6H_4	H	H	**2a**	Me	Et	81 (16) **3g**
8	**1c**	4-MeC_6H_4	H	H	**2c**	CF_3	Et	(52)[a] **3h**
9	**1d**	4-$O_2NC_6H_4$	H	H	**2a**	Me	Et	79 **3i**
10	**1e**	4-$MeOC_6H_4$	H	H	**2a**	Me	Et	66 **3j**
11	**1f**	2-BrC_6H_4	H	H	**2a**	Me	Et	65 **3k**
12	**1g**	Ph	Me	H	**2a**	Me	Et	72 **3l**
13	**1h**	Ph	*N*-Phthalimido	H	**2a**	Me	Et	40[b] **3m**
14	**1i**	Ph	Benzotriazol-1-yl	H	**2a**	Me	Et	79 **3n**
15	**1j**	Ph	Ph	Ph	**2a**	Me	Et	75 **3o**
16	**1k**	Ph	2,2′-Carbonylbisphenyl		**2a**	Me	Et	74 **3p**
17	**1l**	Ph	2,2′-Biphenylene		**2a**	Me	Et	59 **3q**, 21 **4q**
18	**1l**	Ph	2,2′-Biphenylene		**2a**	Me	Et	75[c] (43) **3q**
19	**1l**	Ph	2,2′-Biphenylene		**2b**	Ph	Et	(33) **3r**, (20) **4r**
20	**1l**	Ph	2,2′-Biphenylene		**2c**	CF_3	Et	(82)[a] **3s**
21	**1m**	Ph	Me	Me	**2a**	Me	Et	43[d] **3t**
22	**1n**	Ph	CO_2Et	H	**2a**	Me	Et	10 **3u**, 70 **4u**
23	**1n**	Ph	CO_2Et	H	**2a**	Me	Et	35[e] **3u**, 29[e] **4u**
24	**1o**	Me	Ph	H	**2a**	Me	Et	40 **3v**, 17 *Z*-**4v**
25	**1p**	Me	CO_2Et	H	**2a**	Me	Et	38 *E*-**4w**, 17 *Z*-**4w**

[a] The compound was synthesized according to method ***A*** using the increased concentration of azirine (see Experimental Part, method ***A***′).
[b] Analytical yield based on ^1H NMR data with $CHBr_2CHBr_2$ as internal standard is 79%.
[c] After reflux of the mixture of oxazine and azadiene for 5 h in ethanol.
[d] Was synthesized by method ***C***.
[e] After reflux of the mixture of oxazine and azadiene for 2.5 h in 1,2-dichloroethane.

rate of diazo compound **2a** and, as a result, under short-term heating of reaction mixture (Scheme 3). In most cases azadienes **4** could be smoothly converted into oxazines **3** by short heating in DCE. To remove traces of azadienes the reaction mixtures, derived from azirines **1a**,**h**–**j** (entries 1, 13–15), were refluxed for an additional 5 min: azadienes formed in these reactions are too labile to be separated from 1,4-2*H*-oxazines, the products of its cyclization. In the case of azirine **1l**, however, the product mixture could be separated by chromatography to give compounds **3q** and **4q** in 59 and 21% yields, respectively (entry 17). Oxazine **3q** can be prepared in 75% yield by reflux of the mixture of compounds **3q** and **4q** in ethanol for 5 h (entry 18). In the reactions of azirines **1n**,**o** along with oxazines **3u**,**v** *Z*- and *E*-azadienes **4u**,**v** were formed (entries 22–24). The configuration of the C=C bond in **4u**,**v** was verified by ^1H 2D NOESY NMR spectroscopy (see Supplementary data). It is noticeable that only *E*-isomer of **4u** derived from the azirine **1n** turns to oxazine **3u** when heated in DCE. Thus, the analytical yields of **3u**/*E*-**4u**/*Z*-**4u** after the completion of the reaction (10 min) of the azirine **1n** with diazo compound **2a**, measured by ^1H NMR with $CHBr_2CHBr_2$ as internal standard, were 11, 33, 38%, while after additional refluxing for 2.5 h in DCE the yields became 36, 2, 37%. The cyclization of *Z*-**4u** to oxazine **3u** was observed in boiling toluene only, but was accompanied by the formation of decomposition products.

In the reaction of ethyl benzoyldiazoacetate **2b** with 2,3-diphenylazirine **1a** (method ***B***) along with oxazine **3b** the corresponding azadiene was also formed but its cyclization rate proved to be lower than that in the similar reaction of acetyl analog **2a** (Table 2). Azadiene **4r** formed from fluorene-spiro-azirine **1l** is stable enough to be isolated easily (entry 19).

The reaction of diazo compound **2a** with ethyl 3-methyl-2*H*-azirine-2-carboxylate **1p** in the presence of $Rh_2(OAc)_4$ gave only isomeric azadienes *E*- and *Z*-**4w** (entry 25). Configurations of the C=C bonds in compounds **4w** were determined by NOESY-experiments (see Supplementary data). According to ^1H NMR spectrum of the reaction mixture *E*- and *Z*-isomers **4w** are formed in 2.3:1 ratio and the formation of oxazine **3w**, under conditions of method ***B***, was not observed. Thus the introduction of alkoxycarbonyl substituents at C^2 of azirine ring results in a decrease of the ability of the azadiene formed to undergo 1,6-cyclization. The rate of cyclization of azadienes **4** decreases as R^2 changes from H to Ar to CO_2Et.

Table 2
The half reaction times of dark cyclization of azadienes **4a**,**b**,**d**,**n**,**p**,**q**,**t** (0.02 M solution, 20 °C in $CDCl_3$)

Oxazine	$t_{1/2}$, h	% of azadiene **4** after irradiation of **3**	Duration of irradiation, min
3a	24.5[a]	81	70
3b	29	100	90
3d	9.5	94	70
3n	8	67	70
3q	9.5	77	70
3p	1	68	35
3t	0.5	34	35

[a] The half reaction time in C_6D_6 at 20 °C is 80 h.

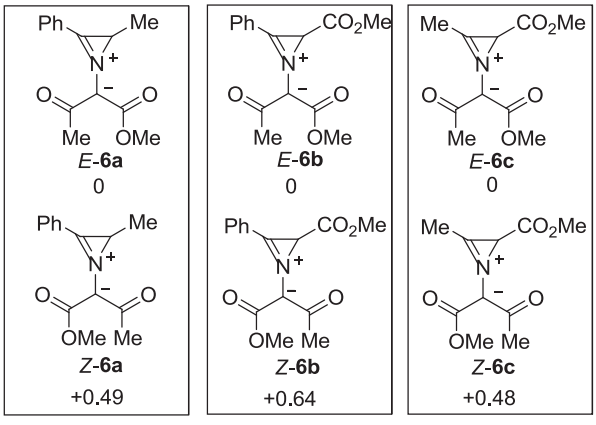
In contrast to diazo compounds **2a**,**b**, ethyl 2-diazo-4,4,4-trifluoroacetoacetate **2c** is rarely utilized in catalytic reactions.[17] A major obstacle to its use is the number of side reactions both of the diazo compound itself and the intermediate carbenoid.[13b,17a] The known reactions of this diazo compound usually failed to proceed in solution of an inert solvent, but provide good results when the substrate is used as a solvent. All our attempts to prepare the corresponding trifluoromethyl-substituted oxazines **3c**,**f** using procedure ***B*** were unsuccessful. Nevertheless, using procedure ***A***, we succeeded in obtaining compounds **3c**,**f**,**h**,**s** in good yields. It was found that the yields are dramatically reduced with the decrease of azirine concentration. Thus, the reduction of the initial concentration of azirine **1a** from 0.33 M to 0.25 M as well as the increase of the concentration of diazo compound **2c** from 0.67 M to 1.0 M and

the rate of addition of diazo compound from 0.35 mL h^{-1} to 1.0 mL h^{-1} causes a decrease in the yield of oxazine **3c** from ca. 80 to ca. 30%. In contrast to reactions of diazo compounds **2a** and **2b** (entries 1, 2), when diazo compound **2c** (entry 3) is used no traces of azadiene **4c** were observed. Therefore, the ability of the substituents R^4 in the acyl fragment of azadienes **4** to facilitate 1,6-cyclization to oxazine are placed in the order: CF_3>CH_3>Ph.

As follows from Table 1, once the aryl substituent in position 3 in azirine is substituted with a methyl group, the barrier to cyclization of azadiene to oxazine rises so much that in some cases (Table 1, entry 25) no cyclization occurs under the reaction conditions. For example, azadiene *E*-**4w** begins to cyclize to oxazine **3w** when refluxed in toluene solution only. Oxazine **3w** is not a very stable compound but was detected by the appearance of the signal of proton H–C^2 at 5.01 δ (see Supplementary data). Even in harsh conditions azadiene *Z*-**4w** is not transformed into the cyclic form.

2.2. Theoretical calculations

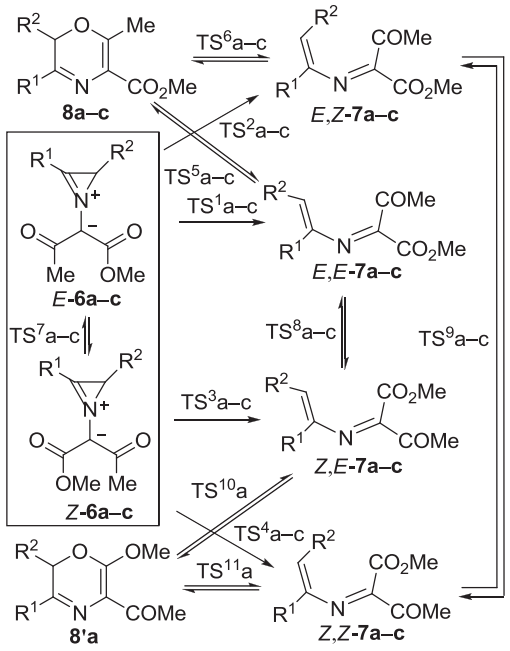
As it follows from ^{1}H NMR and TLC azadienes **4** and oxazines **3** in the reaction are formed in succession. Azadienes **4**, as was stated above, are in many cases very reactive compounds and the rates of their conversion to oxazines **3** are influenced by the nature of substituents R^1, R^2, R^3. We supposed that the reaction sequence leading to oxazines **3** involves the generation of a Rh(II)-carbenoid, whose interaction with azirine **1** gives azirinium ylides **5**, ring opening of azirine ring with the formation of azadienes **4**, followed by 1,6-electrocyclization (Scheme 3). To prove this reaction sequence, as well as to elucidate the influence of the azirine structure on product distribution and stereoselectivity of azadiene formation, quantum-chemical calculations of transformations of model ylides **6a**–**c** (Scheme 4) were carried out at the DFT B3LYP/6-31G(d) level by using the Gaussian 09[18] suite of quantum chemical programs. Geometry optimizations of intermediates, transition states, reactants, and products in 1,2-dichloroethane solutions were performed using PCM model (see Supplementary data). Stationary points on the respective potential-energy surfaces were characterized at the same level of theory by evaluating the corresponding Hessian indices. Careful verification of the unique imaginary frequencies for transition states was carried out to check whether the frequency indeed pertains to the desired reaction coordinate. Intrinsic reaction coordinates (IRC) were calculated to authenticate all transition states.



Scheme 4. Relative free energies (kcal mol^{-1}) of *E*- and *Z*-isomers of ylides **6a**–**c** in W-conformations.

The calculations were carried out both for *E*-ylides *E*-**6a**–**c** and their *Z*-isomers *Z*-**6a**–**c**. Me, Ph and CO_2Me substituents at C^2 and C^3 of the azirine ring were included in the calculations because of their dramatic influence on the above stated product distribution. Besides, we hoped that computations of the possible transformations of ylides **6a**–**c** with such substitution patterns would allow the determination of the stereochemistry of intermediate azadienes, since because of their high reactivity an experimental solution to the problem would be difficult.

The geometries of ylides **6a**–**c**, azadienes *E*,*E*-, *E*,*Z*-, *Z*,*E*- and *Z*,*Z*-**7a**–**c** (differing one from another by the configurations of C=N and C=C bonds), 1,4-oxazines **8a**–**c**,**8′a**, as well as the transition states of ring opening of ylides **6a**–**c** (TS^1–TS^4), 1,6-cyclizations of azadienes **7a**–**c** in oxazines **8a**–**c**,**8′a** (TS^5, TS^6, TS^{10}, TS^{11}), *E*,*Z*-isomerization of ylides **6a**–**c** (TS^7) and *E*,*Z*-isomerization of azadienes **7a**–**c** (TS^8, TS^9) were optimized at the DFT B3LYP/6-31G(d) level using the PCM solvent model for 1,2-dichloroethane. In designations of azadiene configurations the first descriptor denotes the configuration of the C=N bond and coincides with the configuration of its ylide precursor, while the second descriptor indicates the configuration of the C=C bond (Scheme 5).



Scheme 5. The transformation of ylides *E*-**6a**–**c** and *Z*-**6a**–**c** into oxazines **8a**–**c**.

A transition states search was carried out for the most stable W-conformations of the ylides and a number of cisoid-conformations (relative to the single C–N bond) of azadienes. These conformations differed from one another by angles of rotation of the acyl and methoxycarbonyl groups. Geometry optimization of azadienes showed that cisoid-conformations for azadienes **7a**,**b** with a phenyl substituent R^1 (dihedral angle in the range from 56 to 76°) are preferable, while the most stable azadienes **7c** with a methyl substituent R^1 can have both a cisoid- and transoid-conformation. The most favorable transition state and most stable azadiene were used for calculations of the activation free energies of each reaction (Figs. 1–3).

Computations show small differences in the free energies between *E*- and *Z*-isomers of **6a**–**c** (Scheme 4) and this gives grounds to assume that both stereoisomers are formed in the reaction. It is known that *E*,*Z*-isomerization of azomethine ylides, realized via rotation around the C–N bond, has a sufficiently high activation barrier and is often not able to compete with some intermolecular processes such as 1,3-dipolar cycloaddition.[19] For all of the calculated azirinium ylides the activation barriers of *E*,*Z*-isomerization exceed the activation barriers of ring opening. From Figs. 1–3

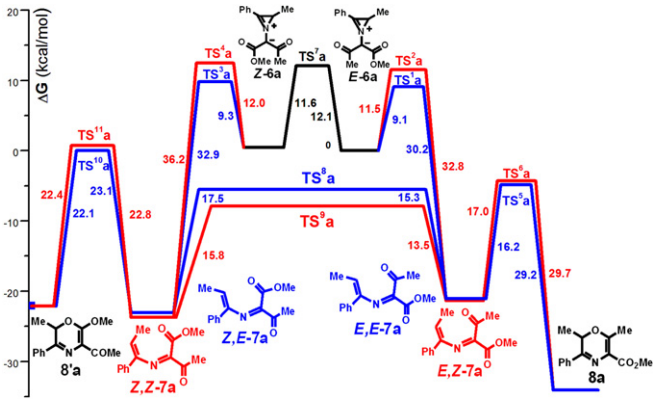


Fig. 1. B3LYP/6-31G(d) free energy profiles (kcal mol^{-1}, 298.15 K) for the transformations of ylides *E*-, *Z*-**6a** to oxazines **8a**, **8′a** in 1,2-dichloroethane.

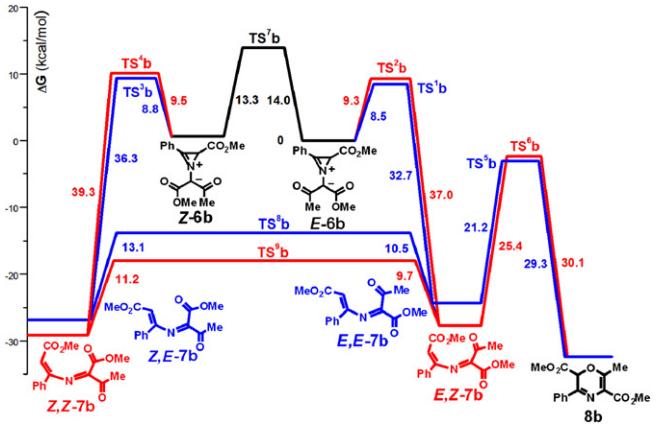


Fig. 2. B3LYP/6-31G(d) free energy profiles (kcal mol^{-1}, 298.15 K) for the transformations of ylides *E*-, *Z*-**6b** to oxazines **8b** in 1,2-dichloroethane.

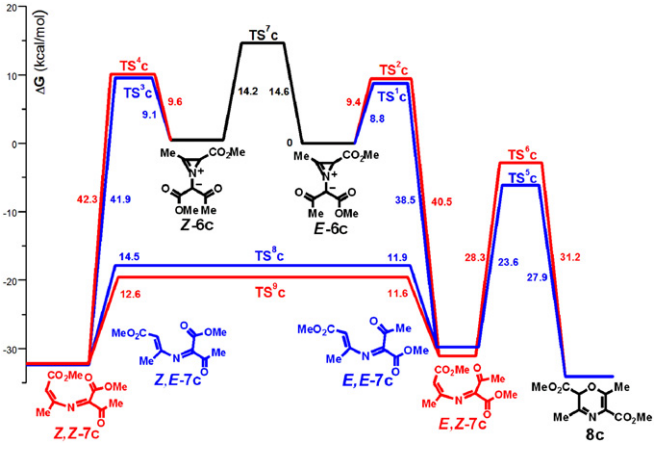


Fig. 3. B3LYP/6-31G(d) free energy profiles (kcal mol^{-1}, 298.15 K) for the transformations of ylides *E*-, *Z*-**6c** to oxazines **8c** in 1,2-dichloroethane.

follows that all the ylides **6** are unstable intermediates that can easily undergo cleavage of the N–C^2 bond of the azirine ring ($\Delta G^{\neq}$=8.5–12.0 kcal mol^{-1}) to give 2-azadienes **7**.

Because of the absence of interconversion between *E*- and *Z*-ylides it follows that the formation of oxazine **8a**–**c** from these isomers proceeds through independent pathways. It is obvious that only the *E*-ylide can be transformed into oxazine **8** in two stages via *E*,*E*- or *E*,*Z*-azadienes **7**, while for the formation of this oxazine from the *Z*-isomer intermediate *Z*,*E*- and *Z*,*Z*-azadienes have to isomerize to *E*,*E*- and *E*,*Z*-azadienes, respectively. Computed activation barriers of N-inversions of *Z*,*E*- and *Z*,*Z*-azadienes **7a** to *E*,*E*- and *E*,*Z*-isomers proved to be slightly lower than the barriers of 1,6-cyclization of the latter to oxazine **8a** (Fig. 1). On changing R^2=Me for CO_2Me in **7** only slightly affects the N-inversion barriers of azadienes **7** (Figs. 2 and 3). Computed N-inversion barriers ($\Delta G^{\neq}$=9.7–17.5 kcal mol^{-1}) are in good agreement with the published values of topomerization barriers of imine systems. According to these results, C=N-containing systems with unsaturated substituents, such as phenyl, cyano, methoxycarbonyl at the nitrogen atom undergo *syn*,*anti*-isomerization with rather low activation barriers 12–16 kcal mol^{-1}.[20]

Formally *Z*,*E*- and *Z*,*Z*-azadienes **7a**–**c** can produce oxazines **8′** (isomers of oxazines **8a**–**c**) via 1,6-electrocyclization with participation of the ester carbonyl. The calculations for the cyclization of azadienes *Z*,*E*- and *Z*,*Z*-**7a** gave the barriers for the formation of oxazine **8′a** as 5.8–6.9 kcal mol^{-1} higher than those for cyclizations with participation of ketonic carbonyl (Fig. 1). The cyclizations of *Z*,*E*- and *Z*,*Z*-azadienes **7a** to oxazine **8′a** are also thermodynamically unfavorable (ΔG=1.0–1.6 kcal mol^{-1}). These results are in good agreement with the experimental observations that 6-alkoxy-substituted oxazines were never formed.

Changing R^2=Me for CO_2Me in azadiene **7** leads to an increase of the cyclization barriers to oxazine by a value of 5–9 kcal mol^{-1}, which makes azadienes with alkoxycarbonyl groups at the both ends of azadiene system kinetically much more stable than the alkyl- and aryl-substituted analogs. This result, which can be rationalized by push-pull stabilization of the iminoacrylate system of the molecule, is in good agreement with the distinctive outcome of the reaction of ethyl azirinecarboxylate **1p** with ethyl diazoacetoacetate (Table 1, entry 25). This change in substitution pattern in the azadiene system results in a decrease of energy difference between cyclic and open chain forms from 13 kcal mol^{-1} for the couple **7a**/**8a** to 4.7–8.1 kcal mol^{-1} for **7b**/**8b**, and to 2.9–4.3 for **7c**/**8c**. Fairly high sensitivity of the equilibrium constant [between colored (yellow or orange) azadiene and colorless (or slightly colored) oxazine forms] to structural changes suggests the possibility of thermochromism for some oxazine/azadiene pairs. In fact, we disclose thermal interconversion of azadiene **3r** to oxazine **4r** (*vide infra*).

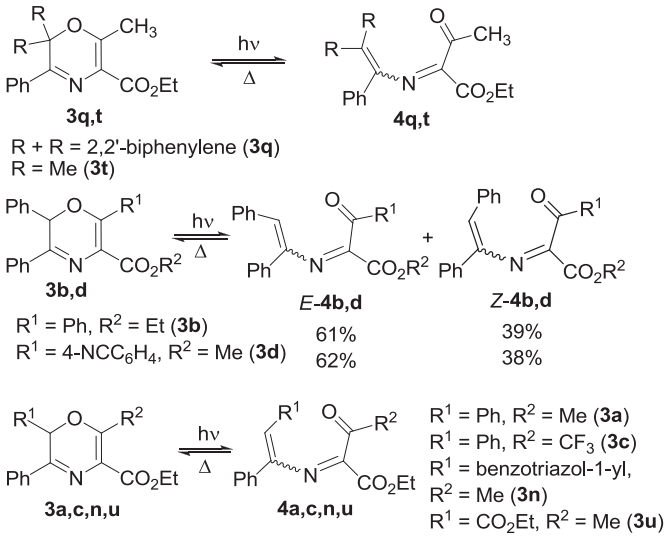
For ylide **6a**, with a Me substituent as R^2, the calculations predict a selective ring opening with preferable formation of azadiene *E*,*E*- and *Z*,*E*-**7a** with the C=C bond in *E*-configuration (Fig. 1). Substitution at the C=C bond with the electron withdrawing group CO_2Me causes a decrease in selectivity of the ring opening (Figs. 2 and 3). It was experimentally shown that in the reaction of azirine **1p** with diazo compound **2a**, which stops after the formation of azadienes *E*-**4w** and *Z*-**4w**, the stereoisomeric products, according to the ^{1}H NMR spectrum, are formed in 2.3:1 ratio (Table 1, entry 25). A little less ratio (1.2:1) of azadienes *E*-**4u** and *Z*-**4u** in the analogous reaction of azirine **1n** was observed with the assumption that oxazine **3u** is the product of cyclization of azadiene *E*-**4u**. The appropriateness of this statement is confirmed by a large difference in calculated values $\Delta G^{\neq}$ of cyclization of azadienes *E*,*E*-**7b** and *E*,*Z*-**7b** to oxazine **8b** (5.8 kcal mol^{-1} in favor of the former one). There is, therefore, every reason to believe that both stereoisomeric azadienes *E*,*E*-**7b** and *E*,*Z*-**7b** are formed in the reaction with low selectivity (both through ylide *E*-**6b** and ylide *Z*-**6b**), the first one of which rapidly cyclizes under reaction conditions. Much longer heating is required for the cyclization of isomeric azadiene *E*,*Z*-**7b** to oxazine **8b**.

Oxazines **3a**–**v** are the result of the isomerization of both *E*- and *Z*-isomeric forms of ylides **5a**–**v** via their azadiene intermediate. Depending on the nature of the substituent at C^4 the latter can be formed either as a single *E*-isomer or a *E*,*Z*-azadiene mixture.

2.3. Photo- and thermochromism of oxazines 3

With the exception of the methyl derivative **3v** the synthesized oxazines **3** are thermally stable compounds both in the solid phase and in solution and do not undergo ring opening in the dark. Their electronic spectra have a long-wave absorption maximum in the region of 315–360 nm, while the open-chained isomers **4** absorb more long-wave radiation at 380–455 nm. Thus the transformation of **3** to **4** may be detected by the change of the color of solution from colorless to bright yellow or orange.

UV irradiation of $CDCl_3$ solutions of oxazines **3q**,**t**, containing two identical substituents at C^2 produces azadienes **4q**,**t** as a single isomer (Scheme 6). Broadened signals of some carbon atoms in the ^{13}C NMR spectrum of compound **4q** show that N-inversion takes place at room temperature and this is in good agreement with the $\Delta G^{\neq}$ values for N-inversion of azadienes **7a**–**c** (vide supra). According to the ^1H NMR spectrum the content of unreacted oxazine **3q** in the photolysate obtained after irradiation of the solution for 2 h at 20 °C is 19%. In contrast to this, the maximal degree of conversion of the 2,2-dimethyl-substituted analog **3t**, which could be achieved under these conditions was only 48% because of the high rate of reverse dark reaction.



Scheme 6. Photochromism of 2-mono- and 2,2-disubstituted oxazines **3a**–**d**,**n**,**q**,**t**,**u**.

Irradiation of 2-monosubstituted oxazines **3b**,**d** for 1.5 h at 20 °C in $CDCl_3$ results in the quantitative formation of the mixture of two isomeric azadienes **4b**,**d** (Scheme 6). Monitoring of the photolytic ring opening of oxazine **3d** and back reaction of cyclization (bleaching) by ^1H NMR shows that the ratio of the isomeric azadienes remains constant in the course of both reactions.

The ^1H NMR spectra of the photolysates obtained after UV irradiation of oxazines **3a**,**c**,**n**,**u** for 1 h show, apart from a signal of starting oxazine, only signals corresponding to the *Z*-azadiene **4a**,**c**,**n**,**u**. Of the oxazines **3a**,**c**,**n**,**u** irradiated the complete conversion of only compound **3u** has been achieved. Irradiation of the trifluoromethyl-substituted oxazine **3c** for 6.5 h produced 55% of opened chain isomer *Z*-**4c** only. Only oxazine **3u** can, therefore, be considered to undergo ring opening with full stereoselectivity, giving exclusively *Z*-isomer. In the remaining cases the formation of some amounts of *E*-isomer should not be excluded since the oxazines **3a**,**c**,**n** observed in photolysates may be the products of rapid cyclization of the *E*-isomers, which according to computations cyclize much faster than *Z*-isomers.

Half-life times ($t_{1/2}$) of the dark cyclization of azadienes **4a**,**b**,**d**,**n**,**q**,**p**,**t** to oxazines **3a**,**b**,**d**,**n**,**q**,**p**,**t** were measured by ^1H NMR (Table 2). Predictably, the rate of cyclization depends upon the nature of the solvent. Thus, the half reaction time of azadiene **4a** bleaching in C_6D_6 is three times greater than that in $CDCl_3$. The rise in temperature accelerates the process: the bleaching of azadiene **4a** is completed in 20 min under reflux in C_6D_6.

We failed to evaluate the stability of azadienes **4e**–**k**, derived from oxazines **3e**–**k**, bearing no substituents at C^2 due to the extremely low concentration of compounds **4e**–**k** in the irradiated solutions.

According to the calculations the difference in energies of cyclic form **8** and open chain form **7** strongly depends upon the nature of the substituent at C^2 of the oxazine ring. Thus on going from the system **8a**/**7a** to system **8c**/**7c** this difference falls from 13.0 to 2.9 kcal mol^{-1} (Figs. 1 and 3). So for oxazines with the appropriate substitution pattern the equilibrium between these two forms is possible at reasonable temperatures. Such equilibria were found for the spirofluorene derivatives **3q**–**s**, which along with their photochromic properties, showed thermochromic activity as well: the intensity of the color of their solutions is changed with temperature variation. Equilibrium constants of thermal ring opening of oxazines **3q**–**s**, measured in $CDCl_3$ solutions by ^1H NMR, decrease in the sequence Ph>CH_3>CF_3 and increase in all cases with the increase of temperature (Table 3). It is noticeable that the equilibrium is most rapidly attained with the trifluoromethyl derivative **3s**.

Table 3
Equilibrium constants of thermal ring opening of oxazines **3q**–**s**

Oxazine	R	K_{eq} (25 °C)	K_{eq} (95 °C)
3q	CH_3	0.02	0.14
3r	Ph	0.11	0.39
3s	CF_3	—	0.02

3. Conclusions

The $Rh_2(OAc)_4$-catalyzed domino reaction of 2*H*-azirines with 2-acyl-2-diazoacetates provides the first synthetic approach to non-fused 2*H*-1,4-oxazines. Several modifications of the general procedure are presented, allowing the use of a wide range of diazo keto esters and azirines. The formation of 2*H*-1,4-oxazines may be reasonably interpreted in terms of the generation of azirinium ylide, its ring opening to 1-acyl-1-(alkoxycarbonyl)-2-azabuta-1,3-diene followed by 1,6-electrocyclization. The last stage can be realized only with the participation of the ketonic carbonyl group of the azadiene having the *E*-configuration of the C=N bond. According to DFT-calculations *Z*- and *E*-isomers of azirinium ylides are more rapidly transformed into the corresponding azadienes than interconvert. Transformation of *Z*-ylide to azadiene with *E*-configuration of the C=N bond proceeds via N-inversion in azadienes, which has a lower activation barrier than the 1,6-cyclization and occurs at ambient temperatures. Ring opening of azirinium ylides with alkyl and aryl substituents on the azirine ring proceeds stereoselectively to give azadienes with C=C bond of *E*-configuration, while ylides with an alkoxycarbonyl group at the same position isomerize to the azadiene unselectively. The substitution pattern of the carbon–carbon double bond in azadienes, as well as its configuration, influences dramatically on their cyclization to oxazines. Azadienes nonsubstituted at C^4 and azadienes with alkyl and aryl groups at this position undergo 1,6-cyclization very easily, while an alkoxycarbonyl group stabilizes an open-chained form and in some cases a new class of stable 2-azadienes, 1-acyl-2-azabuta-1,3-diene-1,4-dicarboxylates, could be isolated. The 1,4-oxazines obtained by this method are the first representatives of monocyclic

2*H*-1,4-oxazine derivatives, which exhibit photo- and thermochromic activity.

4. Experimental section

4.1. General methods

Melting points were determined on a hot stage microscope and are uncorrected. ^{1}H (300 MHz) and ^{13}C (75 MHz) NMR spectra were measured in $CDCl_3$ on Bruker DPX 300 spectrometer. Chemical shifts (δ) are reported in parts per million downfield from tetramethylsilane. Physical constants and spectral data for compounds **3a**,**g**, **4a** presented in preliminary report.[12] Electrospray ionization mass spectra were measured on a Bruker micrOTOF mass spectrometer. Elemental analysis was performed on a Hewlett–Packard 185B CHN-analyser. IR spectra were recorded on an SPECORD M80 spectrometer for solutions in $CHCl_3$. UV spectra were measured on an SHIMADZU UV-1800 spectrophotometer for solutions in EtOH. Silica gel Merck 60 was used for column chromatography. Thin-layer chromatography (TLC) was conducted on aluminia sheets precoated with SiO_2 ALUGRAM SIL G/UV_{254}. Photochemical experiments were carried out with a mercury lamp Tungsram HGOK 400 (main radiation bands 310, 360, 365 nm). Azirines were prepared according to published procedures: **1a**,[21] **1b**, **1c**, and **1e**,[22] **1d**,[23] **1f**,[24] **1g**,[25] **1h**,[26] **1k**,[27] **1l**,[28] **1m**,[29] **1n**,[30] **1o**,[31] **1p**.[32] Diazo keto esters **2** were synthesized according to published procedures: **2a** and **2b**,[33] **2c**.[34]

4.2. General procedures for preparation of oxazines 3a–v and azadienes 4u–w

Method ***A*** *(for reactions of acetyl- and benzoyldiazoacetates)*. A 1.0 M solution of diazo compound **2a**,**b** in anhydrous benzene was added dropwise with a syringe at a rate of 1.0 mL h^{-1} to a stirred 0.25 M solution of azirine **1a**–**c**,**l** and $Rh_2(OAc)_4$ (5 mol % on azirine) in anhydrous benzene at reflux under argon until the azirine was consumed completely (control by TLC). The solvent was removed under vacuum and the residue was purified by column chromatography on silica gel (eluent hexane/EtOAc) to give, after crystallization from the solvent indicated below, compounds **3a**,**b**,**e**,**g** **q**,**r**,**4r**.

Method ***A′*** (*for reactions of trifluoroacetyldiazoacetate*). A 0.67 M solution of ethyl 2-diazo-4,4,4-trifluoro-3-oxobutanoate **2c** in anhydrous benzene was added dropwise with a syringe at a rate 0.35 mL h^{-1} to a stirred 0.33 M solution of azirine **1a**–**c**,**l** (0.5 mmol) and $Rh_2(OAc)_4$ (5 mol % on azirine) in anhydrous benzene at reflux under argon until the azirine was consumed completely (control by TLC). The reaction solution was diluted with a mixture hexane/EtOAc (15:1) and filtered through a pad of neutral Al_2O_3 (15 g) eluting the product using the same mixture. Compounds **3c**,**f**,**h**,**s** were obtained as colorless solids after recrystallization from the solvent indicated below.

Method ***B***. Stoichiometric amounts of azirine **1a**–**l**,**n**–**p** and diazo compound **2a**,**b**,**d** in anhydrous 1,2-dichloroethane (DCE) (0.25 M solution of each component) were heated to reflux under an argon atmosphere and then $Rh_2(OAc)_4$ (5 mol %) was added. The mixture was stirred under reflux until nitrogen evolution stopped (from 5 min for diazo compound **2a**,**d** to 15 min for diazo compound **2b**), and then the next equivalents of diazo compound (1.0 M solution in anhydrous DCE) were added consecutively every 5 min (diazo compound **2a**,**d**) or 15 min (diazo compound **2b**) until the azirine was consumed completely (control by TLC). The resulting mixture was evaporated under reduced pressure and the residue was purified by column chromatography on silica gel (eluent hexane/EtOAc) to give after recrystallization from the appropriate solvent oxazines **3a**,**b**,**d**,**e**,**g**,**i**–**q**,**u**,**v**.

Oxazine **3t** was prepared according to method ***C*** (vide infra).

*4.2.1. Ethyl 2,3,6-triphenyl-2H-1,4-oxazine-5-carboxylate (**3b**).* Compound **3b** was prepared according to the procedure ***A*** from azirine **1a** (97 mg, 0.5 mmol) and diazo compound **2b** (327 mg, 1.5 mmol) in anhydrous benzene to afford 89 mg (45%) of oxazine **3b**. Yellowish solid, mp 122–124 °C (hexane/Et_2O); [Found: C, 78.19; H, 5.44; N, 3.55. $C_{25}H_{21}NO_3$ requires C, 78.31; H, 5.52; N, 3.65]; R_f (20% EtOAc/hexane) 0.27; λ_{max} (EtOH, ε) 230 (17,550), 247infl, 285sh, 354 nm (13,660); ν_{max} ($CHCl_3$) 3020, 1710 (C=O), 1575, 1500, 1455, 1385, 1340, 1200, 1105 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.09 (3H, t, *J* 7.1 Hz), 4.06–4.24 (2H, m), 6.53 (1H, s), 7.33–7.56 (13H, m), 7.92–8.00 (2H, m); δ_C (75 MHz, $CDCl_3$) 13.8, 60.5, 72.9, 120.9, 127.1, 127.7, 128.3, 128.7 (2C), 129.0, 129.6, 129.7, 130.6, 131.5, 132.7, 134.1, 135.2, 150.1, 151.7, 165.5. Compound **3b** (77 mg, 39%) was also prepared according to the procedure ***B*** from azirine **1a** (100 mg, 0.51 mmol) and diazo compound **2b** (339 mg, 1.53 mmol).

*4.2.2. Ethyl 2,3-diphenyl-6-trifluoromethyl-2H-1,4-oxazine-5-carboxylate (**3c**).* Compound **3c** was prepared according to the procedure ***A′*** from azirine **1a** (97 mg, 0.5 mmol) and diazo compound **2c** (130 mg, 0.62 mmol) in anhydrous benzene to afford 156 mg (83%) of oxazine **3c**. White solid, mp 87–88 °C (hexane/Et_2O); [Found: C, 63.99; H, 4.23; N, 3.64. $C_{20}H_{16}F_3NO_3$ requires C, 64.00; H, 4.30; N, 3.73]; R_f (20% EtOAc/hexane) 0.36; λ_{max} (EtOH, ε) 229 (11,790), 245 (10,850), 322 nm (10,980); ν_{max} ($CHCl_3$) 3045, 2995, 1735 (C=O), 1595, 1580, 1460, 1380, 1320, 1200, 1165, 1130, 1070 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.34 (3H, t, *J* 7.1 Hz), 4.25–4.42 (2H, m), 6.49 (1H, s), 7.39–7.55 (8H, m), 7.93–7.97 (2H, m); δ_C (75 MHz, $CDCl_3$) 13.8, 61.8, 72.2, 119.7 (q, *J* 273.7 Hz), 124.9 (q, *J* 2.6 Hz), 127.6, 127.9, 128.86, 128.93, 130.0, 132.0, 132.6, 134.2, 136.8 (q, *J* 38.6 Hz), 154.6 (q, *J* 1.1 Hz), 163.2.

*4.2.3. Methyl 6-(4-cyanophenyl)-2,3-diphenyl-2H-1,4-oxazine-5-carboxylate (**3d**).* Compound **3d** was prepared according to the procedure ***B*** from azirine **1a** (60 mg, 0.31 mmol) and diazo compound **2d** (216 mg, 0.93 mmol) in anhydrous DCE to afford 96 mg (79%) of oxazine **3d**. Yellowish solid, mp 151–164 °C (dec) (Et_2O); [Found: C, 76.17; H, 4.36; N, 7.17. $C_{25}H_{18}N_2O_3$ requires C, 76.13; H, 4.60; N, 7.10]; R_f (20% EtOAc/hexane) 0.16; λ_{max} (EtOH, ε) 238 (23,250), 274infl, 363 nm (15,020); ν_{max} ($CHCl_3$) 2230 (C≡N), 1715 (C=O), 1600, 1580, 1500, 1450, 1435, 1330, 1205, 1195, 1095 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 3.75 (3H, s), 6.53 (1H, s), 7.41–7.51 (10H, m), 7.63–7.66 (2H, m), 7.93–7.96 (2H, m); δ_C (75 MHz, $CDCl_3$) 52.0, 72.9, 113.6, 118.3, 121.6, 127.2, 128.2, 128.8, 129.2, 130.0, 130.3, 131.3, 131.5, 133.5, 134.7, 136.9, 149.6, 151.5, 165.2.

*4.2.4. Ethyl 6-methyl-3-phenyl-2H-1,4-oxazine-5-carboxylate (**3e**).* Compound **3e** was prepared according to the procedure ***B*** from azirine **1b** (117 mg, 1 mmol) and diazo compound **2a** (468 mg, 3 mmol) in anhydrous DCE to afford 178 mg (73%) of oxazine **3e**. The preparation according to the procedure ***A*** yielded 27 mg (11%) of oxazine **3e**. Colorless solid, mp 45–47 °C (hexane/Et_2O); ν_{max} ($CHCl_3$) 3050, 1715 (C=O), 1590, 1475, 1395, 1330, 1235, 1110 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.40 (3H, t, *J* 7.3 Hz), 2.39 (3H, s), 4.35 (2H, q, *J* 7.3 Hz), 4.80 (2H, s), 7.35–7.50 (3H, m), 7.80–7.91 (2H, m); δ_C (75 MHz, $CDCl_3$) 14.3, 17.8, 60.5, 61.9, 120.5, 126.5, 128.6, 130.5, 134.9, 148.2, 157.5, 165.7; HRMS (ESI-TOF): MH$^+$, found 246.1130. $C_{14}H_{16}NO_3$ requires 246.1125.

*4.2.5. Ethyl 3-phenyl-6-trifluoromethyl-2H-1,4-oxazine-5-carboxylate (**3f**).* Compound **3f** was prepared according to the procedure ***A′*** from azirine **1b** (62 mg, 0.53 mmol) and diazo compound **2c** (147 mg, 0.7 mmol) in anhydrous benzene to afford 99 mg (62%) of oxazine **3f**. Colorless solid, mp 78–79 °C (hexane/Et_2O); [Found: C, 56.25; H, 4.06; N, 4.69. $C_{14}H_{12}F_3NO_3$ requires C, 56.19; H, 4.04; N, 4.68]; R_f (20% EtOAc/hexane) 0.34; λ_{max} (EtOH, ε) 228 (8810), 235sh, 245 (8080), 322 nm (8770); ν_{max} ($CHCl_3$) 3050, 2995, 1735 (C=O), 1595, 1570,

1460, 1385, 1330, 1325, 1290, 1200, 1160, 1130 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.40 (3H, t, *J* 7.1 Hz), 4.40 (2H, q, *J* 7.1 Hz), 4.92 (2H, s), 7.46–7.58 (3H, m), 7.90–7.97 (2H, m); δ_C (75 MHz, $CDCl_3$) 13.9, 61.9, 62.4, 119.6 (q, *J* 273.7 Hz), 125.8 (q, *J* 2.5 Hz), 127.5, 128.9, 132.1, 133.5, 139.6 (q, *J* 38.4 Hz), 153.2 (q, *J* 1.2 Hz), 163.3.

*4.2.6. Ethyl 3-(4-methylphenyl)-6-trifluoromethyl-2H-1,4-oxazine-5-carboxylate (**3h**).* Compound **3h** was prepared according to the procedure ***A***′ from azirine **1b** (66 mg, 0.5 mmol) and diazo compound **2c** (130 mg, 0.62 mmol) in anhydrous benzene to afford 82 mg (52%) of oxazine **3h**. Colorless solid, mp 78–79 °C (hexane); [Found: C, 57.24; H, 4.52; N, 4.47. $C_{15}H_{14}F_3NO_3$ requires C, 57.51; H, 4.50; N, 4.47]; R_f (20% EtOAc/hexane) 0.37; λ_{max} (EtOH, ε) 232 (10,180), 239sh, 252 (9040), 326 nm (12,620); ν_{max} ($CHCl_3$) 3040, 3000, 1730 (C=O), 1590, 1570, 1325, 1315, 1290, 1205, 1160, 1140, 1120 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.39 (3H, t, *J* 7.3 Hz), 2.43 (3H, s), 4.40 (2H, q, *J* 7.3 Hz), 4.90 (2H, s), 7.29 (2H, d, *J* 8.7 Hz), 7.84 (2H, d, *J* 8.7 Hz); δ_C (75 MHz, $CDCl_3$) 13.9, 21.6, 61.9, 62.4, 120.1 (q, *J* 273.5 Hz), 126.3 (q, *J* 2.7 Hz), 127.6, 129.7, 130.8, 142.9, 139.8 (q, *J* 38.3 Hz), 153.6 (q, *J* 1.1 Hz), 163.4.

*4.2.7. Ethyl 6-methyl-3-(4-nitrophenyl)-2H-1,4-oxazine-5-carboxylate (**3i**).* Compound **3i** was prepared according to the procedure ***B*** from azirine **1d** (60 mg, 0.37 mmol) and diazo compound **2a** (174 mg, 1.11 mmol) in anhydrous DCE to afford 85 mg (79%) of oxazine **3i**. Light-yellow solid, mp 143–146 °C (Et_2O); [Found: C, 58.05; H, 4.91; N, 9.63. $C_{14}H_{14}N_2O_5$ requires C, 57.93; H, 4.86; N, 9.65]; R_f (20% EtOAc/hexane) 0.18; λ_{max} (EtOH, ε) 239 (10,670), 264sh, 363 nm (10,620); ν_{max} ($CHCl_3$) 3008, 2850, 1708 (C=O), 1566, 1526 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.42 (3H, t, *J* 7.3 Hz), 2.44 (3H, s), 4.38 (2H, q, *J* 7.3 Hz), 4.86 (2H, s), 8.04 (2H, d, *J* 8.7 Hz), 8.31 (2H, d, *J* 8.7 Hz); δ_C (75 MHz, $CDCl_3$) 14.4, 18.0, 60.8, 61.7, 121.1, 123.9, 127.4, 140.5, 145.3, 148.6, 158.8, 165.2.

*4.2.8. Ethyl 3-(4-methoxyphenyl)-6-methyl-2H-1,4-oxazine-5-carboxylate (**3j**).* Compound **3j** was prepared according to the procedure ***B*** from azirine **1e** (60 mg, 0.41 mmol) and diazo compound **2a** (192 mg, 1.23 mmol) in anhydrous DCE to afford 74 mg (66%) of oxazine **3j** as a yellowish oil. ν_{max} ($CHCl_3$) 2984, 2940, 2844, 1704 (C=O), 1600, 1516 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.40 (3H, t, *J* 7.3 Hz), 2.38 (3H, s), 3.85 (3H, s), 4.34 (2H, q, *J* 7.3 Hz), 4.77 (2H, s), 6.95 (2H, d, *J* 8.7 Hz), 7.82 (2H, d, *J* 8.7 Hz); δ_C (75 MHz, $CDCl_3$) 14.4, 17.9, 55.3, 60.5, 61.8, 114.0, 120.4, 127.6, 128.2, 148.0, 157.0, 161.5, 165.9; HRMS (ESI-TOF): MNa^+, found 298.1085. $C_{15}H_{17}NNaO_4$ requires 298.1050.

*4.2.9. Ethyl 3-(2-bromophenyl)-6-methyl-2H-1,4-oxazine-5-carboxylate (**3k**).* Compound **3k** was prepared according to the procedure ***B*** from azirine **1f** (80 mg, 0.41 mmol) and diazo compound **2a** (256 mg, 1.64 mmol) in anhydrous DCE to afford 86 mg (65%) of oxazine **3k**. Colorless solid, mp 81–83 °C (hexane/Et_2O); [Found: C, 51.93; H, 4.36; N, 4.45. $C_{14}H_{14}BrNO_3$ requires C, 51.87; H, 4.35; N, 4.32]; R_f (20% EtOAc/hexane) 0.27; λ_{max} (EtOH, ε) 241 (11,010), 313 nm (5990); ν_{max} ($CHCl_3$) 3030, 2990, 2850, 1705 (C=O), 1575, 1440, 1390, 1370, 1325, 1295, 1100, 1070, 1025 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.38 (3H, t, *J* 7.2 Hz), 2.42 (3H, s), 4.37 (2H, q, *J* 7.2 Hz), 4.76 (2H, s), 7.25–7.31 (1H, m), 7.35–7.41 (1H, m), 7.57–7.63 (2H, m); δ_C (75 MHz, $CDCl_3$) 14.5, 17.8, 60.7, 64.2, 121.3, 121.5, 127.6, 131.1, 131.8, 132.8, 138.1, 149.4, 158.4, 165.4.

*4.2.10. Ethyl 2,6-dimethyl-3-phenyl-2H-1,4-oxazine-5-carboxylate (**3l**).* Compound **3l** was prepared according to the procedure ***B*** from azirine **1g** (70 mg, 0.53 mmol) and diazo compound **2a** (284 mg, 1.82 mmol) in anhydrous DCE to afford 99 mg (72%) of oxazine **3l** as a yellowish oil, which solidified on cooling. Mp 39–42 °C; ν_{max} ($CHCl_3$) 3030, 2990, 2930, 1700 (C=O), 1585, 1450, 1370, 1320, 1305, 1110, 1090, 1075 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.39 (3H, d, *J* 6.9 Hz), 1.42 (3H, t, *J* 7.2 Hz), 2.39 (3H, s), 4.36 (2H, q, *J* 7.2 Hz), 5.48 (1H, q, *J* 6.9 Hz), 7.41–7.48 (3H, m), 7.86–7.89 (2H, m); δ_C (75 MHz, $CDCl_3$) 14.4, 15.3, 18.6, 60.5, 67.6, 118.6, 126.4, 128.6, 130.4, 134.7, 151.5, 154.8, 165.9; HRMS (ESI-TOF): MH^+, found 260.1301. $C_{15}H_{18}NO_3$ requires 260.1281.

*4.2.11. Ethyl 6-methyl-3-phenyl-2-phthalimido-2H-1,4-oxazine-5-carboxylate (**3m**).* Compound **3m** was prepared according to the procedure ***B*** from azirine **1h** (37 mg, 0.14 mmol) and diazo compound **2a** (175 mg, 1.12 mmol) in anhydrous DCE to afford 50 mg (72%) of oxazine **3m**, contaminated with products of diazo compound decomposition. After double crystallization from Et_2O/hexane mixture 22 mg (40%) of compound **3m** was obtained as a yellowish solid. Mp 117–119 °C; [Found: C, 67.48; H, 4.66; N, 7.24. $C_{22}H_{18}N_2O_5$ requires C, 67.69; H, 4.65; N, 7.18]; R_f (20% EtOAc/hexane) 0.14; λ_{max} (EtOH, ε) 248 (12,640), 306 (10,540), 323 nm (10,540); ν_{max} ($CHCl_3$) 3030, 2985, 1780, 1730 (C=O), 1705 (C=O), 1600, 1470, 1450, 1370, 1350, 1325, 1115, 1090 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.46 (3H, t, *J* 7.2 Hz), 2.42 (3H, s), 4.41 (2H, q, *J* 7.2 Hz), 7.26 (1H, s), 7.35–7.41 (3H, m), 7.73–7.80 (2H, m), 7.84–7.95 (4H, m); δ_C (75 MHz, $CDCl_3$) 14.4, 18.4, 60.7, 68.4, 118.4, 124.1 (2C), 126.2, 128.7, 130.7, 131.3, 134.2, 134.8, 143.9, 154.3, 165.6, 166.2.

*4.2.12. Ethyl 2-(benzotriazol-1-yl)-6-methyl-3-phenyl-2H-1,4-oxazine-5-carboxylate (**3n**).* Compound **3n** was prepared according to the procedure ***B*** from azirine **1i** (50 mg, 0.214 mmol) and diazo compound **2a** (200 mg, 1.28 mmol) in anhydrous DCE to afford 61 mg (79%) of oxazine **3n**. Colorless solid, mp 101–102 °C (hexane); [Found: C, 66.28; H, 5.06; N, 15.44. $C_{20}H_{18}N_4O_3$ requires C, 66.29; H, 5.01; N, 15.46]; R_f (20% EtOAc/hexane) 0.19; λ_{max} (EtOH, ε) 230 (10,900), 246 (9900), 262infl, 294 (7200), 318 nm (7200); ν_{max} ($CHCl_3$) 3004, 2940, 2876, 1708 (C=O), 1612, 1590 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.45 (3H, t, *J* 7.1 Hz), 2.36 (3H, s), 4.43 (2H, q, *J* 7.1 Hz), 7.33–7.55 (6H, m), 7.86 (1H, s), 7.83–7.90 (2H, m), 8.10 (1H, d, *J* 8.0 Hz); δ_C (75 MHz, $CDCl_3$) 14.4, 18.2, 61.0, 75.4, 110.1, 119.4, 120.4, 124.7, 126.5, 128.8, 129.0, 131.2, 131.3, 133.7, 143.4, 146.6, 153.9, 165.0.

*4.2.13. Ethyl 6-methyl-2,2,3-triphenyl-2H-1,4-oxazine-5-carboxylate (**3o**).* Compound **3o** was prepared according to the procedure ***B*** from azirine **1j** (135 mg, 0.5 mmol) and diazo compound **2a** (468 mg, 3 mmol) in anhydrous DCE to afford 149 mg (75%) of oxazine **3o**. Colorless solid, mp 122–126 °C (Et_2O); [Found: C, 78.60; H, 5.90; N, 3.60. $C_{26}H_{23}NO_3$ requires C, 78.57; H, 5.83; N, 3.52]; R_f (20% EtOAc/hexane) 0.34; λ_{max} (EtOH, ε) 245 (12,050), 321 nm (7050); ν_{max} ($CHCl_3$) 3065, 3035, 3010, 2930, 1700 (C=O), 1600, 1580, 1495, 1450, 1375, 1330, 1180, 1095 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.35 (3H, t, *J* 7.2 Hz), 2.38 (3H, s), 4.29 (2H, q, *J* 7.2 Hz), 7.10–7.23 (3H, m), 7.26–7.36 (10H, m), 7.45–7.38 (2H, m); δ_C (75 MHz, $CDCl_3$) 14.4, 18.5, 60.5, 83.3, 120.8, 127.5, 128.0, 128.7, 128.9, 129.0, 129.3, 137.3, 140.2, 152.5, 155.9, 165.4.

*4.2.14. Ethyl 6′-methyl-10-oxo-3′-phenyl-9H-spiro[anthracene-9,2′-[1,4]-oxazine]-5′-carboxylate (**3p**).* Compound **3p** was prepared according to the procedure ***B*** (instead of chromatographic purification recrystallization from ethanol was used) from azirine **1k** (148 mg, 0.5 mmol) and diazo compound **2a** (468 mg, 2 mmol) in anhydrous DCE to afford 156 mg (74%) of oxazine **3p**. Colorless solid, mp 185–190 °C (dec) (hexane/CH_2Cl_2); [Found: C, 76.51; H, 4.96; N, 3.46. $C_{27}H_{21}NO_4$ requires C, 76.58; H, 5.00; N 3.31]; R_f (20% EtOAc/hexane) 0.25; λ_{max} (EtOH, ε) 248 (23,480), 279sh, 335 nm (8340); ν_{max} ($CHCl_3$) 3020, 2990, 1700 (C=O), 1670, 1600, 1590, 1460, 1375, 1320, 1256, 1094 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.47 (3H, t, *J* 7.3 Hz), 2.30 (3H, s), 4.43 (2H, q, *J* 7.3 Hz), 6.96–7.17 (3H, m), 7.24–7.34 (2H, m), 7.50–7.65 (6H, m), 8.40 (2H, d, *J* 6.5 Hz); δ_C (75 MHz, $CDCl_3$) 14.5, 19.0, 60.7, 75.7, 114.9, 127.8, 127.89, 127.93,

129.2, 129.6, 129.8, 130.0, 134.5, 135.3, 140.9, 151.1, 154.9, 165.9, 182.4.

*4.2.15. Ethyl 6′-methyl-3′-phenyl-2H′,9′H-spiro[fluorene-2,9′-[1,4]-oxazine]-5′-carboxylate (**3q**) and ethyl 2-[fluoren-9-ylidene(phenyl) methylimino]-3-oxobutanoate (**4q**).* From azirine **1l** (133 mg, 0.5 mmol) and diazo compound **2a** (312 mg, 2 mmol) using anhydrous DCE as a solvent according to the procedure **B** 117 mg (59%) of oxazine **3q** and 42 mg (21%) of compound **4q** were obtained. When a mixture of compounds **3q** and **4q** was further refluxed in ethanol for 5 h 147 mg (75%) of oxazine **3q** was obtained after crystallization from hexane/Et_2O.

Compound **3q**. Colorless solid, mp 133–134 °C (hexane/Et_2O); [Found: C, 78.72; H, 5.36; N, 3.31. $C_{26}H_{21}NO_3$ requires C, 78.97; H, 5.35; N, 3.54]; R_f (20% EtOAc/hexane) 0.29; λ_{max} (EtOH, ε) 232 (26,970), 252sh, 278infl, 293infl, 336 nm (5680); ν_{max} ($CHCl_3$) 3030, 3000, 1710 (C=O), 1610, 1590, 1460, 1380, 1340, 1300, 1280, 1290, 1270, 1185, 1170, 1105 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.47 (3H, t, *J* 7.3 Hz), 2.38 (3H, s), 4.44 (2H, q, *J* 7.3 Hz), 7.02–7.07 (2H, m), 7.14–7.24 (5H, m), 7.41–7.47 (4H, m), 7.74 (2H, d, *J* 7.5 Hz); δ_C (75 MHz, $CDCl_3$) 14.5, 18.8, 60.7, 83.2, 119.0, 120.5, 125.8, 127.6, 127.7, 128.7, 129.6, 130.5, 135.6, 140.0, 144.6, 152.4, 157.8, 165.9.

Compound **4q** was also obtained with 19% impurity of oxazine **3q** after UV irradiation of **3q** for 2 h at 20 °C in $CDCl_3$ (it cyclzes into oxazine **3q** during recording of ^{13}C NMR spectrum). Its ^1H and ^{13}C NMR spectra are identical with those of azadiene obtained from azirine **1l** and diazo compound **2a**.

Compound **4q**. Orange oil; R_f (20% EtOAc/hexane) 0.36; λ_{max} (EtOH, ε) 449 nm (2740); δ_H (300 MHz, $CDCl_3$) 1.03 (3H, m), 2.74 (3H, s), 3.71–3.86 (2H, m), 6.26 (1H, d, *J* 8.0 Hz), 6.84–6.90 (1H, m), 7.19–7.26 (1H, m) 7.29–7.53 (5H, m), 7.65–7.75 (2H, m), 8.06–8.10 (1H, m); δ_C (75 MHz, $CDCl_3$) 13.5, 25.8, 61.8, 119.47, 119.52, 124.9, 126.7, 127.2, 127.9, 128.5, 128.8, 130.6, 131.3, 134.3, 136.1, 137.3, 140.4, 141.1, 144.8, 156.4, 163.5, 197.0.

*4.2.16. Ethyl 3′,6′-diphenyl-2H′,9′H-spiro[fluorene-2,9′-[1,4]-oxazine]-5′-carboxylate (**3r**) and ethyl 2-[fluoren-9-ylidene(phenyl)methylimino]-3-oxo-3-phenylpropanoate (**4r**).* Oxazine **3r** (75 mg, 33%) and azadiene **4r** (47 mg, 20%) were prepared according to the procedure **A** from azirine **1l** (135 mg, 0.5 mmol) and diazo compound **2b** (327 mg, 1.5 mmol) in anhydrous benzene.

Compound **3r**. Light yellow solid; mp 120–142 °C (dec) (Et_2O); [Found: C, 81.62; H, 5.08; N, 3.20. $C_{31}H_{23}NO_3$ requires C, 81.38; H, 5.07; N, 3.06]; R_f (20% EtOAc/hexane) 0.23; λ_{max} (EtOH, ε) 225 (32,650), 232sh, 259 (23,940), 359 nm (9810); ν_{max} ($CHCl_3$) 3068, 2980, 1720 (C=O), 1610, 1560, 1540, 1488, 1450, 1368, 1336, 1292, 1260, 1228, 1208, 1184, 1112, 1096, 1060 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.21 (3H, t, *J* 7.2 Hz), 4.29 (2H, q, *J* 7.2 Hz), 7.06–7.11 (2H, m), 7.16–7.24 (3H, m), 7.26–7.34 (4H, m), 7.35–7.42 (3H, m), 7.44–7.50 (4H, m), 7.79 (2H, d, *J*=7.3 Hz); δ_C (75 MHz, $CDCl_3$) 13.9, 60.8, 83.4, 120.5, 120.8, 126.0, 127.7, 127.8, 128.7, 129.5, 129.8, 130.3, 130.5, 132.5, 135.4, 140.2, 144.2, 154.0, 154.2, 165.7.

Azadiene **4r**. Orange solid; mp 108–111 °C (Et_2O/hexane); R_f (20% EtOAc/hexane) 0.32; λ_{max} (EtOH, ε) 455 nm (2500); δ_H (300 MHz, $CDCl_3$) 1.15–1.35 (3H, m, CH_3), 4.30–4.50 (2H, m, CH_2), 6.10–6.26 (2H, m), 6.75–6.86 (2H, m), 6.88–7.65 (13H, m), 8.05–6.26 (1H, m).

*4.2.17. Ethyl 3′-phenyl-6′-trifluoromethyl-2H′,9′H-spiro[fluorene-2,9′-[1,4]-oxazine]-5′-carboxylate (**3s**).* Compound **3s** was prepared according to the procedure ***A′*** from azirine **1l** (144 mg, 0.54 mmol) and diazo compound **2c** (220 mg, 1.05 mmol) in anhydrous benzene to afford 199 mg (82%) of oxazine **3s**. Colorless solid, mp 130–132 °C (hexane/Et_2O); [Found: C, 69.53; H, 4.20; N, 2.78. $C_{26}H_{18}F_3NO_3$ requires C, 69.48; H, 4.04; N, 3.12]; R_f (20% EtOAc/hexane) 0.34; λ_{max} (EtOH, ε) 225 (29,420), 232 (26,600), 258 (20,550), 273infl, 288infl, 328 nm (7060); ν_{max} ($CHCl_3$) 3050, 2950, 1730 (C=O), 1595, 1580, 1465, 1385, 1355, 1320, 1290, 1200, 1175, 1040 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.45 (3H, t, *J* 7.2 Hz), 4.47 (2H, q, *J* 7.2 Hz), 7.09 (2H, t, *J* 7.6 Hz), 7.21–7.30 (5H, m), 7.41 (2H, d, *J* 7.6 Hz), 7.49 (2H, t, *J* 7.6 Hz), 7.76 (2H, d, *J* 7.6 Hz); δ_C (75 MHz, $CDCl_3$) 13.9, 62.1, 83.2, 119.5 (q, *J* 274.1 Hz), 120.7, 124.5 (q, *J* 2.5 Hz), 125.8, 127.9, 128.1, 128.9, 130.9, 131.1, 134.4, 139.0 (q, *J* 38.7 Hz), 140.2, 142.9, 158.8 (q, *J* 0.8 Hz), 163.6.

*4.2.18. Ethyl 2,2,6-trimethyl-3-phenyl-2H-1,4-oxazine-5-carboxylate (**3t**).* Method ***C***: A solution of azirine **1m** (40 mg, 0.28 mmol) and diazo compound **2a** (196 mg, 1.26 mmol) in anhydrous DCE (3 mL) was heated to reflux under argon and then $Rh_2(OAc)_4$ (1.8 mg, 1.5 mol %) was added. The mixture was refluxed for 10 min after what a solution of diazo compound **2a** (47 mg, 0.3 mmol) in DCE (1.5 mL) and $Rh_2(OAc)_4$ (1.8 mg, 1.5 mol %) were sequentially added. After accomplishing of this operation one time else the azirine vanished (according to monitoring by TLC). The isolation of oxazine **3t** was carried out according to the procedure ***A***. White solid, mp 101–103 °C (hexane); [Found: C, 70.26; H, 7.15; N, 5.09. $C_{16}H_{19}NO_3$ requires C, 70.31; H, 7.01; N, 5.12]; R_f (20% EtOAc/hexane) 0.29; λ_{max} (EtOH, ε) 240 (11,600), 312 nm (6360); ν_{max} ($CHCl_3$) 3390, 2985, 1700 (C=O), 1580, 1460, 1445, 1370, 1330, 1290, 1275, 1125, 1090 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.37 (3H, t, *J* 7.2 Hz), 1.55 (6H, s), 2.37 (3H, s), 4.34 (2H, q, *J* 7.2 Hz), 7.35–7.42 (3H, m), 7.52–7.58 (2H, m); δ_C (75 MHz, $CDCl_3$) 14.4, 18.7, 24.5, 60.4, 75.0, 119.1, 128.0, 128.1, 129.3, 136.8, 156.27, 156.31, 165.8.

*4.2.19. Diethyl 6-methyl-3-phenyl-2H-1,4-oxazine-2,5-dicarboxylate (**3u**), ethyl (E)-3-{[1-(ethoxycarbonyl)-2-oxopropylidene]amino}-3-phenyl-2-propenoate (E-**4u**), and ethyl (Z)-3-{[1-(ethoxycarbonyl)-2-oxopropylidene]amino}-3-phenyl-2-propenoate (Z-**4u**).* According to the procedure ***B*** from azirine **1n** (95 mg, 0.5 mmol) and diazo compound **2a** (195 mg, 1.26 mmol) using anhydrous DCE as a solvent 16 mg (10%) of oxazine **3u** and 111 mg (70%) of unseparated mixture of azadienes *E*-**4u** *И* *Z*-**4u** were obtained. When the reaction mixture was additionally refluxed under inert atmosphere for 2.5 h the chromatography (hexane/EtOAc, 10:1) produced 55 mg (35%) of compound **3u** and 46 mg (29%) of compound *Z*-**4u**.

Compound **3u**. Pale yellow oil; λ_{max} (EtOH, ε) 230 (8400), 246 (9300), 327 nm (6100); ν_{max} ($CHCl_3$) 3030, 2990, 1750 (C=O), 1705 (C=O), 1585, 1450, 1370, 1330, 1210, 1170, 1100, 1020 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.18 (3H, t, *J* 7.2 Hz), 1.39 (3H, t, *J* 7.2 Hz), 2.49 (3H, s), 4.06–4.28 (2H, m), 4.34 (2H, q, *J* 7.2 Hz), 5.87 (1H, s), 7.40–7.50 (3H, m), 7.96–8.04 (2H, m); δ_C (75 MHz, $CDCl_3$) 13.8, 14.3, 18.1, 60.6, 62.2, 69.5, 120.1, 127.4, 128.4, 130.6, 134.8, 145.8, 156.5, 165.2, 166.3; HRMS (ESI-TOF): MH^+, found 318.1332. $C_{17}H_{20}NO_5$ requires 318.1336.

Compound *Z*-**4u**. Yellow oil; λ_{max} (EtOH, ε) 220 (12,100), 248 (11,200), 273 (13,300), 340 (1000), 400 nm (250); ν_{max} ($CHCl_3$) 3035, 2990, 1745 (C=O), 1710 (C=O), 1605, 1575, 1448, 1370, 1340, 1230, 1175, 1065, 1020 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.19 (3H, t, *J* 7.2 Hz), 1.28 (3H, t, *J* 7.2 Hz), 2.64 (3H, s), 4.16 (2H, q, *J* 7.2 Hz), 4.23 (2H, q, *J* 7.2 Hz), 5.63 (1H, s), 7.37–7.46 (3H, m), 7.48–7.54 (2H, m); δ_C (75 MHz, $CDCl_3$) 13.8, 14.1, 25.7, 60.1, 62.1, 98.0, 126.4, 128.7, 130.6, 134.0, 156.2, 158.4, 160.7, 165.1, 195.9; HRMS (ESI-TOF): MH^+, found 318.1356. $C_{17}H_{20}NO_5$ requires 318.1336.

Compound *E*-**4u** (not separated from *Z*-**4u**): δ_H (300 MHz, $CDCl_3$) δ 1.14 (3H, t, *J* 7.2 Hz), 1.34 (3H, t, *J* 7.2 Hz), 2.49 (3H, s), 4.07 (2H, q, *J* 7.2 Hz), 4.38 (2H, q, *J* 7.2 Hz), 5.40 (1H, s), 7.37–7.54 (5H, m); δ_C (75 MHz, $CDCl_3$) 13.9, 14.0, 24.7, 60.2, 62.4, 103.0, 127.9, 128.5, 129.8, 133.1, 154.3, 161.0, 161.7, 165.0, 196.0.

*4.2.20. Ethyl 3,6-dimethyl-2-phenyl-2H-1,4-oxazine-5-carboxylate **3v** and ethyl 2-[(1-methyl-2-phenylvinyl)imino]-3-oxobutanoate Z-**4v**.* According to the procedure ***B*** from azirine **1o** (66 mg, 0.5 mmol) and diazo compound **2a** (156 mg, 1 mmol) using

anhydrous DCE as a solvent 52 mg (40%) of oxazine **3v** and 22 mg (17%) of compound *Z*-**4v** were obtained.

Compound **3v**. Pale yellow oil; λ_{max} (EtOH, ε) 230 (9900), 289 nm (3600); ν_{max} ($CHCl_3$) 3030, 2985, 2930, 1710 (C=O), 1595, 1495, 1455, 1380, 1370, 1310, 1150 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.36 (3H, t, *J* 7.1 Hz), 2.02 (3H, s), 2.27 (3H, s), 4.32 (2H, q, *J* 7.1 Hz), 5.28 (1H, s), 7.30–7.42 (5H, m); δ_C (75 MHz, $CDCl_3$) 14.4, 18.3, 23.3, 60.5, 76.1, 118.2, 127.6, 128.8, 129.2, 135.1, 153.7, 155.9, 165.6. HRMS (ESI-TOF): MH^+, found 260.1264. $C_{15}H_{18}NO_3$ requires 260.1281.

Compound *Z*-**4v**. Orange oil; λ_{max} (EtOH, ε) 255 (9300), 350 (1700), 421 nm (700); ν_{max} ($CHCl_3$) 3030, 3010, 2990, 2930, 1736 (C=O), 1710 (C=O), 1495, 1445, 1370, 1360, 1300, 1058 cm^{-1}; δ_H (300 MHz; $CDCl_3$; Me_4Si) δ_H (300 MHz, $CDCl_3$) 1.19 (3H, t, *J* 7.2 Hz), 2.10 (3H, d, *J* 1.1 Hz), 2.56 (3H, s), 4.23 (2H, q, *J* 7.2 Hz), 5.95 (1H, q, *J* 1.1 Hz), 7.16–7.24 (1H, m), 7.26–7.33 (4H, m); δ_C (75 MHz, $CDCl_3$) 13.8, 21.9, 25.0, 61.9, 118.0, 126.8, 128.1, 129.1, 135.6, 142.0, 155.8, 163.8, 197.0; HRMS (ESI-TOF): MNa^+, found 282.1109. $C_{15}H_{17}NNaO_3$ requires 282.1101.

*4.2.21. Ethyl (E)-3-{[1-(ethoxycarbonyl)-2-oxopropylidene]amino}-2-butenoate (E-**4w**) and ethyl (Z)-3-{[1-(ethoxycarbonyl)-2-oxopropylidene]amino}-2-butenoate (Z-**4w**).* According to the procedure **B** from azirine **1p** (87 mg, 0.69 mmol) and diazo compound **2a** (265 mg, 1.7 mmol) using anhydrous DCE as a solvent 67 mg (38%) of compound *E*-**4w** and 29 mg (17%) of compound *Z*-**4w** were obtained.

Compound *E*-**4w**. Yellow oil; R_f (20% EtOAc/hexane) 0.38; λ_{max} (EtOH, ε) 230 (5700), 313 (500), 380 nm (200); ν_{max} ($CHCl_3$) 3030, 2985, 2940, 1745 (C=O), 1710 (C=O), 1630, 1450, 1370, 1340, 1300, 1145, 1095, 1060 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.28 (3H, t, *J* 7.2 Hz), 1.30 (3H, t, *J* 7.2 Hz), 2.38 (3H, d, *J* 1.1 Hz), 2.47 (3H, s), 4.17 (2H, q, *J* 7.2 Hz), 4.32 (2H, q, *J* 7.2 Hz), 5.14 (1H, br s); δ_C (75 MHz, $CDCl_3$) 14.0, 14.2, 17.2, 24.6, 60.0, 62.2, 101.4, 154.5, 161.6, 162.1, 166.0, 196.0; HRMS (ESI-TOF): MNa^+, found 278.1018; $C_{12}H_{17}NNaO_3$ requires 278.0999.

Compound *Z*-**4w**. Yellow oil; R_f (20% EtOAc/hexane) 0.33; λ_{max} (EtOH, ε) 237 (6700), 342 (250), 380 nm (150); ν_{max} ($CHCl_3$) 3030, 2985, 1740 (C=O), 1710 (C=O), 1625, 1445, 1370, 1300, 1140, 1060 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 1.23 (3H, t, *J* 7.2 Hz), 1.30 (3H, t, *J* 7.2 Hz), 2.08 (3H, d, *J* 1.1 Hz), 2.54 (3H, s), 4.08 (2H, q, *J* 7.2 Hz), 4.30 (2H, q, *J* 7.2 Hz), 5.05 (1H, d, *J* 1.1 Hz); δ_C (75 MHz, $CDCl_3$) 14.0, 14.1, 18.9, 22.1, 59.8, 62.2, 98.8, 154.2, 158.7, 161.1, 164.9, 196.2; HRMS (ESI-TOF): MH^+, found 256.1182. $C_{12}H_{18}NO_5$ requires 256.1179.

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Supplementary data

^1H, ^{13}C NMR spectra of all new compounds, ^1H 2D NOESY NMR spectra of compounds **4u**, *Z*-**4v** and Cartesian coordinates of optimized structures can be found online. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2013.03.106. These data include MOL files and InChiKeys of the most important compounds described in this article.

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