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Pseudopericyclic 1,5- versus Pericyclic 1,4- and 1,6-Electrocyclization in Electron-Poor 4-Aryl-2-azabuta-1,3-dienes: Indole Synthesis from 2*H*-Azirines and Diazo Compounds

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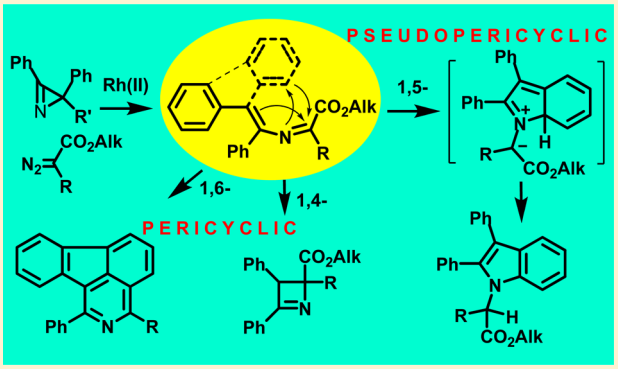
Supporting Information

ABSTRACT: Transformations of 2-azabuta-1,3-dienes, formed in $Rh_2(OAc)_4$-catalyzed reactions of diazo carbonyl compounds with 2*H*-azirines, dramatically depend on the nature of substituents. 4,4-Diphenyl-2-azabuta-1,3-dienes with two electron-acceptor substituents at C^1 undergo thermal 1,5-cyclization to give indoles in good yields. The increase in electron-withdrawing ability of C^1-substituents facilitates the reaction that proceeds via pseudopericyclic 1,5-electrocyclization of 2-azabutadiene into 7a*H*-indolium ylide followed by prototropic shift. 3,4-Diphenyl-2-azabuta-1,3-dienes, resulting from reaction of 2,3-diphenyl-2*H*-azirine and diazo compounds, do not produce indoles via 1,5-cyclization due to the *trans*-configuration of the 4-Ph-group and the nitrogen, but undergo 1,4-cyclization to 2,3-dihydroazetes. 1,6-Cyclization into 2*H*-1,4-oxazines with participation of the oxygen of ester or amide group at C^1 of corresponding 2-azabuta-1,3-dienes does not take place due to kinetic and thermodynamic reasons. Instead of this, 1,6-electrocyclization with participation of phenyl substituent at C^4 of the 2-azabuta-1,3-dienes, providing isoquinoline derivatives, can occur at elevated temperatures. The DFT-calculations (mPWB1K/6-31+G(d,p)) confirm the dependence of 2-azabuta-1,3-diene transformation type on the nature of substituents.



INTRODUCTION

Electron-poor 2-azabuta-1,3-dienes are valuable buildings blocks for the preparation of a wide range of cyclic and acyclic nitrogen-containing compounds.[1] Activation of 2-azabutadiene fragment by electron-withdrawing groups makes these compounds active substrates for (4 + 2)-, (2 + 3)-, (2 + 2)- and (2 + 1)-cycloadditions. These intermolecular reactions along with nucleophile-initiated cyclizations of activated 2-azabutadienes[2] allow constructing a great variety of functionalized 3−6-membered heterocycles. In contrast, only few examples of intramolecular transformations of 2-azabutadienes are known and limited to 1,6- and 1,4-electrocyclizations. Among them are 1,6-cyclization of 2-azabuta-1,3-dienes, generated in situ by aza-Wittig reaction from iminophosphoranes,[3] to pyridine,[4] isoquinoline,[5] pyrazolo[4,3-*c*]pyridine,[6] and quinazoline derivatives.[7] Rather new Rh(II)-catalyzed domino reaction of α-diazo esters **2** with 2*H*-azirines **1** made accessible 2-azadienes **3** with two or more electron-withdrawing groups, some of which showed unusual reactivity (Scheme 1).[8] In particular, 1-acyl-substituted 2-azabuta-1,3-dienes, in contrast to stable 1-alkoxycarbonyl-2-azabuta-1,3-dienes,[9] are extremely labile and prone to undergo 1,6-cyclization into 2*H*-1,4-oxazines **4** at room temperature.[10] Besides, an unusual 1,4-cyclization of 3,4-diphenyl-substituted azadiene **3** (Ar = R^1 = Ph, R^2 = H, R^3 = CO_2Me) giving rise to dihydroazete **5a** in good yield under mild conditions was reported.[9] Recently it was found that 4-halogen-2-azabutadiene-1,1,4-tricarboxylates also cyclize into strained dihydroazete system, but under more harsh conditions.[11] To the best of our knowledge the thermal 1,5-cyclizations of 4-aryl-2-azabuta-1,3-dienes are unknown.

In the present work we report a new reaction of electron-poor 2-azabuta-1,3-dienes giving rise to *N*-substituted indoles. There are a lot of different methods for the construction of indole core, which were summarized by Taber and Tirunahari in nine synthetic strategies.[12] An approach to indole system via the formation of N−C^{7a} bond by formal substitution of *ortho*-hydrogen in aryl-group may involve thermolysis or catalysis of azido styrenes,[13] thermal or catalytic ring expansion of 2-aryl-2*H*-azirines,[14] PIFA-oxidative cyclization of 2-aryl-substituted enamines[15] and isonitrile-mediated[16] or Pd-catalyzed cyclization of β-nitrostyrenes.[17] The reaction of indole formation from 2-azabutadienes found in this work is the first example of generation of nitrogen ylide from azapolyene precursor and, in

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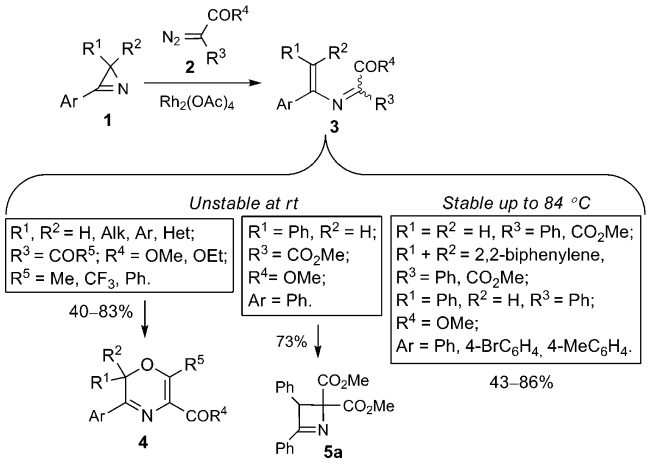
Scheme 1. Synthesis and Thermal Stability of Known 2-Azadienes



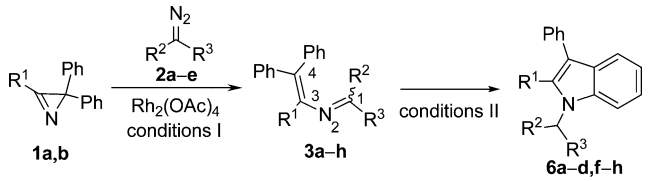
contrast to all mentioned above reactions, does not operate with energy-rich starting material or reagents. To gain insight into the reaction mechanism and structural factors governing the cyclization of 2-azabutadienes the DFT-calculations of energy barriers for their 1,4-, 1,5- and 1,6-cyclization processes were carried out.

RESULTS AND DISCUSSION

The reactivity of 2-azabuta-1,3-dienes strongly depends upon the nature of substituents at atom C^4. Thus, 4-unsubstituted azadiene derived from 3-phenyl-2*H*-azirine and dimethyl diazomalonate **2a** is thermally stable, whereas its 4-phenyl-substituted analogue is extremely unstable compound rapidly cyclizing to 2,3-dihydroazete **5a** (Scheme 1).[9] Assuming that accumulation of aryl substituents at C^4 of 2-azadiene promotes the 1,4-cyclization we tried to synthesize 3,3-diphenyl-substituted 2,3-dihydroazete from 2,2,3-triphenyl-2*H*-azirine **1a** and dimethyl diazomalonate **2a** under $Rh_2(OAc)_4$-catalysis. Initially, the reaction was carried out by slow addition of **2a** to a mixture of **1a** and $Rh_2(OAc)_4$ in 1,2-dichloroethane (DCE) at 84 °C (method B). Unexpectedly a mixture of azadiene **3a** and indole **6a** in 12:1 ratio was obtained in 93% overall yield. No traces of dihydroazete derivative were detected in the reaction mixture. A separate experiment showed that in the absence of the catalyst at temperatures below 100 °C dimethyl diazomalonate **2a** is stable and does not react with azirine **1a**. It was also found that indole **6a** is formed from azadiene **3a** under refluxing in DCE and the ratio **6a**/**3a** is increased with the increase of heating time. When the reaction was carried out by addition of the catalyst (5 mol %) to a mixture of **1a** and **2a** in refluxing 1,2-dichloroethane (method A) azadiene **3a** was the only product. It was isolated by column chromatography on silica gel in 72% yield (Table 1, entry 1). Refluxing toluene solution of pure **3a** for 45 min gave indole **6a** in 81% yield (Table 1, entry 1).

We explored a range of azirines and diazo substrates for this reaction. In the following discussion, the product distribution will be reported, complemented by DFT calculations on the mechanisms. Then, the initial ring openings to the azadienes will be reported, along with DFT calculations on these reactions. Azadienes **3b–d** prepared from azirine **1a** and diazo compounds **2b–d** also smoothly isomerize to indoles **6b–d** under heating. Cyclization of cyano-substituted azadiene **3b** proceeds even at 84 °C to give quantitatively indole **6b** (Table 1, entry 2). This compound was also synthesized from azirine **1a** without isolation of azadiene **3b** in 76% yield (see Experimental Section). At the same time, for the cyclization of azadienes **3c,d** with less electron-withdrawing substituents, CF_3 and $CONMe_2$, much higher temperature is required (Table 1, entries 3, 4). Besides, in these cases a decrease in product yields from quantitative to 64–65% is observed (Table 1, entries 3, 4). Azadiene **3e** with only one acceptor substituent at atom C^1 is relatively thermally stable (Table 1, entry 5). The rate of cyclization of azadienes **3** into indoles **6** slightly increases as R^1 changes from Ph to Me, and in this case less time is required for the reaction to be completed (Table 1, entries 6–8). Reactions of azirine **1b** with diazo compounds **2a–c** carried out without isolation of azadienes **3f–h** produce good yields of indoles **6f–h** (Table 1, entries 6–8). Azadienes **3f,h** are stable at room temperature and, in principle, can be isolated in pure form by

Table 1. $Rh_2(OAc)_4$-Catalyzed Reaction of Azirines 1a,b with Diazo Compounds 2a–e (Conditions I) and Thermal Cyclization of 2-Azadienes 3a–h to Indoles 6a–d,f–h (Conditions II)



entry	1	2	R^1	R^2	R^3	conditions I[a]	yield of **3** (%)	conditions II	yield of **6** (%)[b]
1	**a**	**a**	Ph	CO_2Me	CO_2Me	DCE, 84 °C, 5 min	72 (**a**)	toluene, 110 °C, 45 min	81 (**a**)
2	**a**	**b**	Ph	CN	CO_2Et	DCE, 40 °C, 13 min	76 (**b**)	DCE, 84 °C, 20 min	100 (**b**)
3	**a**	**c**	Ph	CF_3	CO_2Et	DCE, 84 °C, 5 min	91 (**c**)	*o*-xylene, 144 °C, 40 min	65 (**c**)
4	**a**	**d**	Ph	CO_2Me	$CONMe_2$	DCE, 84 °C[c]	74 (**d**)[d]	*o*-xylene, 144 °C, 4 h	64 (**d**)
5	**a**	**e**	Ph	Ph	$CONMe_2$	DCE, 84 °C[c]	70 (**e**)	*o*-xylene, 144 °C, 4 h	0 (**e**)
6	**b**	**a**	Me	CO_2Me	CO_2Me	DCE, 84 °C, 8 min	– (**f**)[e,f]	DCE, 84 °C, 1.25 h	76 (**f**)[g]
7	**b**	**b**	Me	CN	CO_2Et	DCE, 40 °C, 5 min	– (**g**)[e,h]	DCE, 84 °C, 15 min	72 (**g**)[g]
8	**b**	**c**	Me	CF_3	CO_2Et	DCE, 84 °C, 3 min	– (**h**)[e]	toluene, 110 °C, 1 h	61 (**h**)[g]

[a]Method A. [b]Prepared from corresponding azadiene **3**. [c]Method B. [d]Compound **3d** was isolated as stereoisomeric mixture in 6.5:1 ratio. [e]Compounds **3f,g,h** were used without further chromatographic purification. [f]According to ^1H NMR spectrum of the reaction mixture azadiene **3f** and indole **6f** were formed in 5.3:1 ratio. [g]The yield calculated on azirine **1b**. [h]Isomerizes into **6g** at rt.

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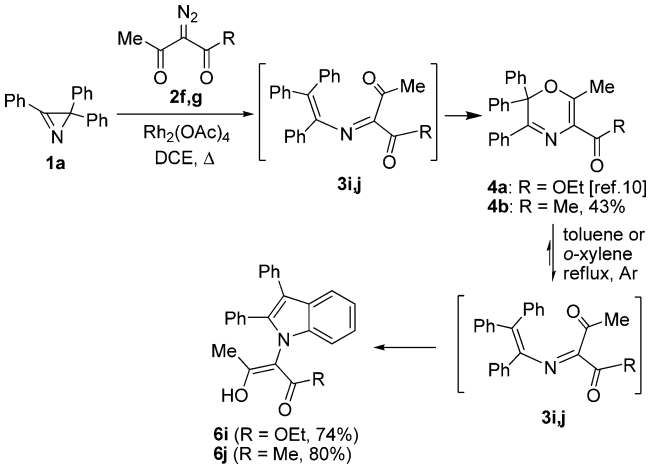
chromatography, whereas cyano-substituted azadiene **3g** cyclizes into indole **6g** within 2 days on storage in solution.

Therefore, azadienes **3a–d,f,h** can be easily synthesized in good yields from 2,2-diphenylazirines **1a,b** and rhodium carbenoids generated from diazo compounds **2a–d** because their cyclization to indoles requires more harsh conditions (see conditions I and conditions II, Table 1). Observed azadiene-indole isomerization prompted us to consider 1-acyl-substituted 2-azadienes **3** (R^2 = COR) as potential precursors of synthetically inaccessible 2-indolylacetoacetic ester and 2-indolylacetylacetone derivatives. However, the problem is that such 2-azadienes cannot be synthesized from azirines **1** and corresponding 2-acyl-2-diazoacetates due to its rapid 1,6-cyclization to 2*H*-1,4-oxazines **4** (Scheme 1).[10] We suggested, that at elevated temperatures 2*H*-1,4-oxazines can reversibly produce azadiene tautomer **3**, which, in turn, can undergo 1,5-cyclization to indole derivative. For verification of this hypothesis oxazines **4a** and **4b** were synthesized. Oxazine **4a** was prepared from azirine **1a** and ethyl 2-diazoacetoacetate **2f** according to the known procedure,[10] while oxazine **4b** was synthesized for the first time from azirine **1a** and 3-diazopentane-2,4-dione **2g** in the presence of $Rh_2(OAc)_4$ in 43% yield (Scheme 2). Refluxing the solution of oxazine **4a** in

Scheme 2. Synthesis of Indoles 6i,j from Oxazines 4a,b



toluene or oxazine **4b** in *o*-xylene gave indoles **6i,j** in good yield. The structures of compounds **6a–d,f–j** were verified by ^1H and ^{13}C NMR spectroscopy, mass-spectrometry and the structure of **6a** was confirmed by X-ray analysis (Figure 1). Indoles **6i,j** exist in enol form in $CDCl_3$ solution.

We supposed that isomerization of 2-azadienes **3a–d,f–j** to indoles **6a–d,f–j** proceeds through indolium ylides **7a** as depicted in Scheme 3 for the compound **3a**. Azadiene **3a** undergoes pseudopericyclic 1,5-cyclization to ylide **7a** followed by 1,8-H-shift into enol of **6a**. To the best of our knowledge it is the first example of concerted transformation of an azapolyene system into a 1,3-dipole. Usually, 1,5-electrocyclization is characteristic of the conjugated 1,3-dipolar systems[18] including azomethine ylides[19] which cyclize into various pyrrole and azole derivatives. The high energy of 1,3-dipolar species is the driving force of these cyclizations. Relatively mild conditions of the isomerization of azadienes **3** into indoles **6** suggests that this process may be referred to as pseudopericyclic 1,5-electrocyclization. Pseudopericyclic reactions Lemal et al.[20] defined as concerted transformations whose

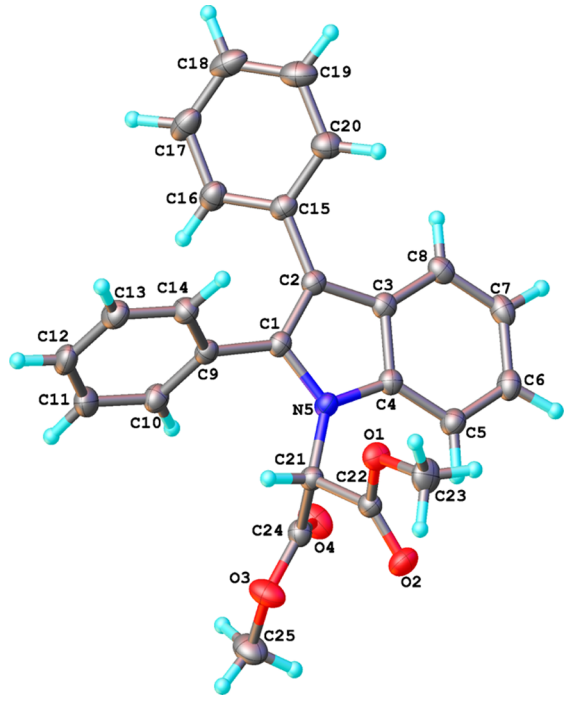
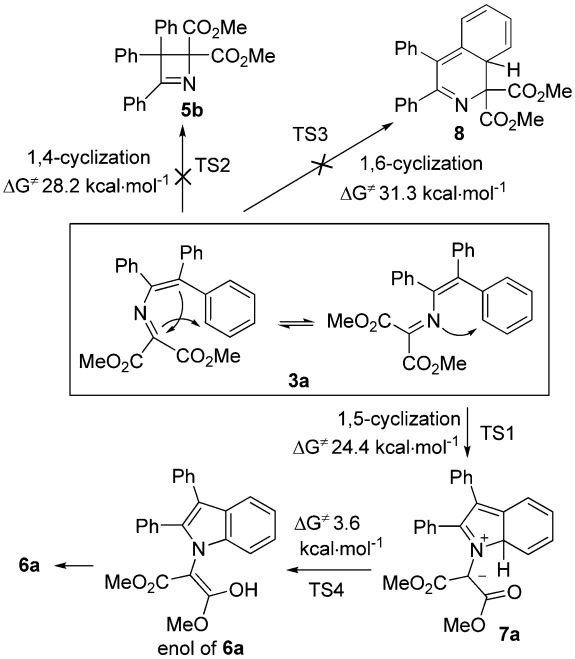


Figure 1. X-ray crystal structure of compound **6a**.

Scheme 3. Free Energy Barriers (DFT mPWB1K/6-31+G(d,p)) for 1,4-, 1,5- and 1,6-Cyclization of 2-Azadiene 3a and Proposed Mechanism for the Formation of Indoles 6



primary changes in bonding occur within a cyclic array of atoms at one (or more) of which nonbonding and bonding atomic orbitals interchange roles. These concerted processes are not governed by the Woodward–Hoffmann rules and characterized by low activation barriers and flattened transition states.[21] This supposition prompted us to carry out the DFT-calculations of the activation barriers for 1,4-, 1,5- and 1,6-cyclizations of azadiene **3a** to indolium ylide **7a**, 2,3-dihydroazete **5b**, and dihydroisoquinoline **8**, respectively, in order to evaluate the competitive ability of these transformations (Scheme 3). The

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calculations were carried out with Gaussian 09[22] at the DFT mPWB1K/6-31+G(d,p) level using the PCM solvent model for 1,2-dichloroethane. All energies mentioned below are calculated values. Activation barrier for 1,5-cyclization of azadiene **3a** to indolium ylide **7a** proved to be sufficiently low (24.4 kcal·mol^{-1}) and can be overcome under reasonable temperatures. The barriers for 1,4-cyclization to dihydroazete **5b** (28.2 kcal·mol^{-1}) and 1,6-cyclization (31.3 kcal·mol^{-1}) to dihydroisoquinoline **8** are higher and these reactions cannot compete with the 1,5-cyclization to indole. The further prototropic shift in ylide **7a** proceeds with a predictable low-activation barrier (3.6 kcal·mol^{-1}) due to the formation of aromatic indole system of the enol form of **6a**. The intrinsic reaction coordinate (IRC) computations showed a conrotatory ring-closure for 1,4-cyclization **3a** → **5b** and disrotatory one for 1,6-cyclization **3a** → **8**. At the same time, there is no disrotatory motion in the 1,5-cyclization of the six-electron system **3a** into indolium ylide **7a** that labels this reaction as pseudopericyclic electrocyclization. To quantify the planarity of cyclic transition state a value of the internal dihedral angle containing the forming bond (Figure 2) can be used.[23] For the pseudopericyclic

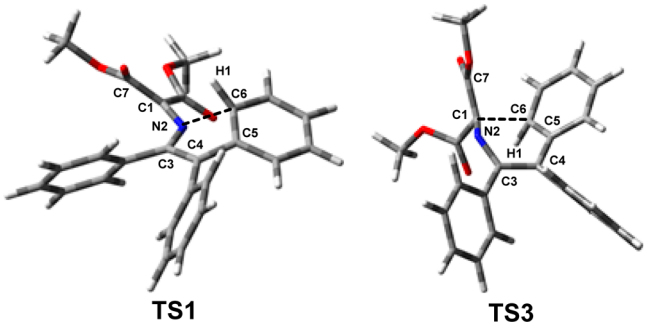


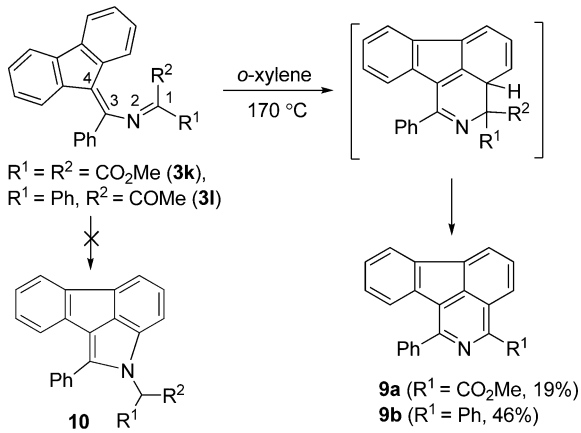
Figure 2. Structures of TS1 and TS3 calculated by mPWB1K/6-31+G(d,p) method.

transition state TS1 the value of dihedral C^6–N^2–C^3–C^4 is 20.8°, while a similar angle C^6–C^1–N^2–C^3 in the less flat pericyclic TS3 is 33.1°. The fact of nonparticipation of the π-orbital of C═N bond in bonding also follows from the lower value of dihedral angle of the C═N bond in transition state TS1 in comparison with those for bond C–CO$_2$Me in TS3. Thus, for TS1 the dihedrals ∠C^1–N^2–C^3–C^6 and ∠H^1–C^6–C^5–N^2 are 139.8 and 84.7°, respectively, while in TS3 the similar angles ∠C^7–C^1–N^2–C^6 and ∠H^1–C^6–C^5–N^2 are 119.4 and 88.4°; i.e., appreciably smaller deviation from 180° of the first angle in TS1 than those for TS3 is observed.

The suggested mechanistic scheme is in a good agreement with experimentally discovered relationship between the temperature required for the cyclization to occur and electron-withdrawing ability of substituents at C^1 atom: cyclization of azadienes with more strong electron-withdrawing R^1 and R^2 substituents can be carried out at lower temperature (Table 1). It can be rationalized in terms of stabilization of anionic center of the ylide **7a** by electron-withdrawing groups, the formation of which, according to computation results, is a rate-determining step. An acceptor ability of one electron-withdrawing group is not sufficient for the successful generation of a 7a*H*-indolium ylide even under harsh conditions.

The nature and the number of aromatic substituents at C^4 of 2-azabutadiene fragment have a dramatic influence on the reactivity of 2-azadienes. The combining of two geminal phenyl groups into fluorene system (compound **3k**) lead to the change of the reaction route. 2-Azabutadiene **3k**, derived from 3-phenyl-2*H*,9′*H*-spiro[azirine-1,9′-fluorene] and dimethyl diazomalonate **2a**,[9] proved to be more stable toward heating than compound **3a**. It transforms at 170 °C in *o*-xylene to 2-azafluoranthene **9a**, the product of 1,6-electrocyclization onto a benzene ring (Scheme 4). The participation of aromatic

Scheme 4. 1,6-Electrocyclization of Azadienes 3k,l to Azafluoranthenes 9a,b



systems in 1,6-electrocyclizations occurring at 140–160 °C are known for 4-aryl-2-azabutadienes, which have additional 3-ethoxycarbonyl-, 3-phenyl- or 3-heteryl substituent.[5,24] This type of cyclization of electron-poor 2-azadienes did not show essential sensibility to electronic effect of substituents at C^1: azadiene **3l** synthesized from 3-phenyl-2*H*,9′*H*-spiro[azirine-1,9′-fluorene] and 1-diazo-1-phenylpropan-2-one **2h** (see Experimental Section) also reacted under similar conditions to afford 2-azafluoranthene **9b** in 46% yield. The change of cyclization type on going from *gem*-diphenyl systems **3a–d,f–j** to fluorene systems **3k,l** can be accounted for by decreased stability of strained indeno[1,2,3-*cd*]indole system **10**.

The main question that arises in connection with the scope of 2-azabutadiene–indole isomerization is why the indole derivative is not formed in analogous reaction of 2,3-diphenyl-2*H*-azirine with dimethyl diazomalonate **2a**? Only 2,3-dihydroazete **5a** in good yield was isolated in this case (Scheme 1).[9] It is obvious that the reactivity of intermediate 2-azabutadiene defines the outcome of the reaction. Having assumed that the result of intramolecular transformation of intermediate azadiene might be depending on substituents at C^4 (numbering of atoms in Scheme 4 and Table 2), which originated from the azirine, we reacted 2*H*-azirines **1c,d** with diazo compounds **2d,e,i,j** in the presence of Rh$_2$(OAc)$_4$ (Table 2).

The reaction of azirine **1c** with 2-diazo-*N*,*N*-dimethyl-2-phenylacetamide **2e** provided azadiene *E*-**11a** as a sole product (Table 2, entry 1). This compound does not cyclize to corresponding indole or dihydroazete in toluene or *o*-xylene even under heating, but smoothly isomerizes across C═N bond to give an equilibrium mixture (1:4) of isomers of *E*-**11a**, which underwent no changes under further heating. Changing Ph-group for electron-withdrawing ester group in diazo compound leads to emergence of 2,3-dihydroazetes **12** among the products of the reaction. Carbenoids, derived from diazo amides **2d,i**, give rise to a mixture of two isomeric, noninterconverting azadienes *Z*-**11b**, *E*-**11b,c** and dihydroazete

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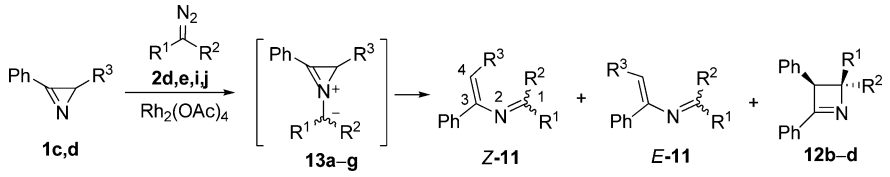
Table 2. $Rh_2(OAc)_4$-Catalyzed Reaction of Azirines 1c,d with Diazo Compounds 2d,e,i,j



entry	azirine	diazo compound	R^1	R^2	R^3	yield of *Z*-**11**	yield of *E*-**11**	yield of **12**[a]
1	**1c**	**2e**	Ph	$CONMe_2$	Ph	–	72 (*E*-**11a**)	–
2	**1c**	**2d**	CO_2Me	$CONMe_2$	Ph	14 (*Z*-**11b**)	29 (*E*-**11b**)[b]	42 (**12b**)[b]
3	**1c**	**2i**	CO_2Me	CON(OMe)Me	Ph	–	2 (*E*-**11c**)[b]	31 (**12c**)[b]
4	**1c**	**2j**	CO_2Me	1-indolylcarbonyl	Ph	–	–	52 (**12d**)
5	**1d**	**2e**	Ph	$CONMe_2$	H	62 (**11e**)	–	
6	**1d**	**2d**	CO_2Me	$CONMe_2$	H	51 (**11f**)[c]	–	
7	**1d**	**2j**	CO_2Me	1-indolylcarbonyl	H	39 (**11g**)[d]	–	

[a]To avoid confusion with letters in numbers of dihydroazetes those that have two geminal ester functions have number **5**, while dihydroazetes with an amide function have number **12**. [b]Equilibrium mixture of *E*-**11** and **12**, rt. [c]Mixture of stereoisomers in 4.3:1 ratio. [d]Mixture of stereoisomers in 3.2:1 ratio. Dimethyl 2,3-di(1*H*-indole-1-carbonyl)-5-phenyl-3,4-dihydro-2*H*-pyrrole-2,3-dicarboxylate was also isolated as byproduct as 1:1 mixture of diastereomers in 18% yield.

12b,c as a sole diastereomer (Table 2, entries 2,3). It is notable, that azadiene *E*-**11b,c** exists in equilibrium with dihydroazete **12b,c** at room temperature, while isomer *Z*-**11b** does not cyclize to **12b** or corresponding indole even under heating. All our attempts to isolate compounds *E*-**11b,c** and **12b,c** in pure form failed. Only mixtures enriched with one of the components were obtained, each of which under storage at room temperature produces an equilibrium mixture, specified in Table 2. Analogous reaction of diazo compound **2j**, containing stronger electron-withdrawing amide-type substituent, 1-indolylcarbonyl group, gave only one product, dihydroazete **12d** (Table 2, entry 4). Dihydroazetes **12b–d** are formed in these reactions as a single (2*RS*,3*SR*)-diastereomer. No traces of the second isomer were detected by ^{1}H NMR analysis of reaction mixtures. The high-field shifted signal in ^{1}H NMR spectra of methyl protons (3.16–3.31 ppm) of CO_2CH_3 which lies in the shielding region of the *cis*-Ph group, shows 2*RS*,3*SR* configuration of the stereocenters. The structure of the compound **12d** was confirmed by X-ray analysis (Figure 3).

From the data of Table 2 it follows that two electron-withdrawing substituent at C^1 atom and *E* configuration of C=C bond in azadiene **11** are two necessary conditions for its successful conversion to dihydroazetes **12** to occur. 4,4-Unsubstituted azadienes **11e–g** do not undergo 1,4-cyclization even at elevated temperatures (Table 2, entries 5–7). As dihydroazete **12** is exclusively originated from azadiene *E*-**11**, it is obvious that, azadiene with *E* configuration of C=C bond is preferably formed in all the reactions of azirine **1c** with diazo carbonyl compounds. The formation of traces of *Z* isomer was observed only in few cases. This stereoselectivity of the process is in a good agreement with the mechanistic scheme involving the intermediate formation of metal-free ylide species **13**. Quantum-chemical calculations of activation barriers (DFT mPWB1K/6-31+G(d,p), PCM for 1,2-dichloroethane) for ring-opening in model ylide **13h** showed that the formation of *E*-isomer is much more favorable than *Z* isomer (Figure 4). This stereoselectivity, evaluated by DFT calculations, is retained for 3-Ph-4-Me- (**11i**), 3-Me-4-Ph- (**11j**) and 3,4-diMe-analogues (**11k**) of azadiene **11h** (see Supporting Information). Theoretically predicted torquoselectivity (2.8–5.2 kcal·mol^{-1}preference for outward transition states TS5(h–k), see Figure 4 and Supporting Information) for all phenyl and methyl substituted 4π-electron ylide systems **13h–k** are in good agreement with stereochemistry of ring-opening of cyclobutene systems for which tendency for outward rotation of substituents increases with the increase of its electron-donating character.[25] From the calculations also unambiguously follows that activation barrier for 1,4-cyclization of 1,1-dialkoxycarbonyl-substituted azadiene **11h** (Figure 4) and **11i–k** (Figures S1–S3, Supporting Information) dramatically depends upon the configuration of C=C bond. In all cases the barriers for 1,4-cyclization of *E* azadiene are significantly lower than that of *Z* isomer, that is in a good agreement with the experimental results obtained for azadienes **11a–d** (Table 2).

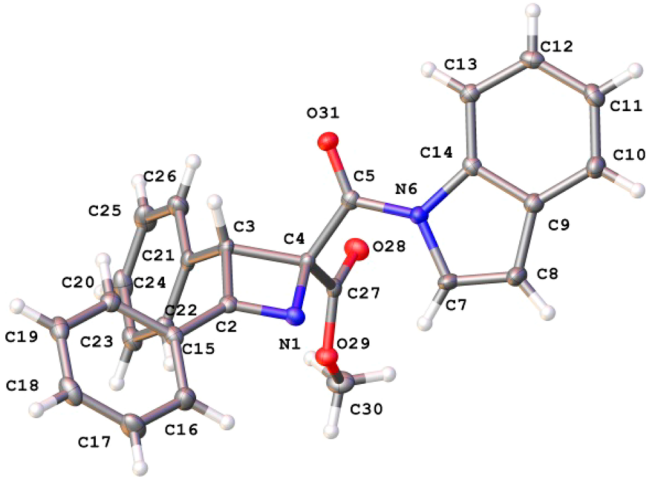


Figure 3. X-ray crystal structure of compound **12d**.

High sensitivity of 1,4-cyclization rate to the configuration of C=C bond of an azadiene is retained when one of the C^1-substituents changes from CO_2Me to CONRR′ (Scheme 5, Figure 5). From the energy profile for the transformation of azirinium ylide generated from 2,3-diphenyl-2*H*-azirine **1c** and diazo amide **2d** (Figure 5) follows that (a) *E* azadiene cyclizes much faster than *Z* isomer, and (b) 1,4-cyclization of azadiene **11b** proceeds with full stereoselectivity: amide group of more stable (*RS*,*SR*)-isomer **12b** is located in *trans* position to Ph.

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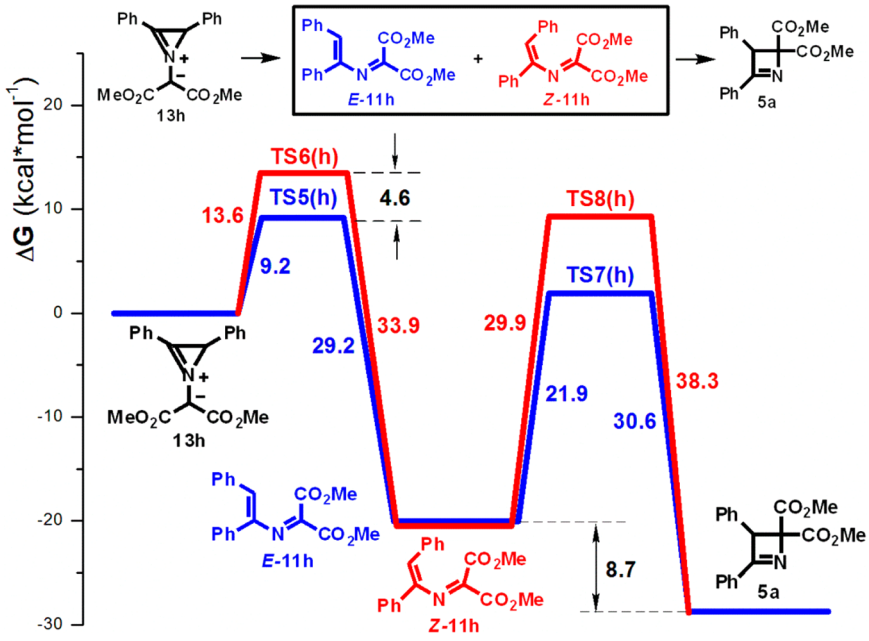
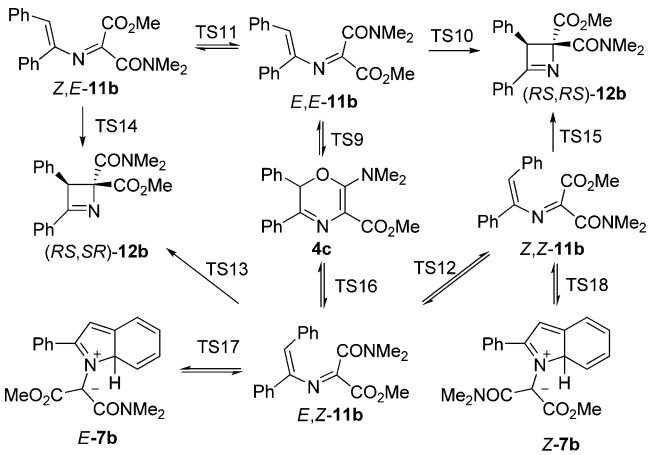


Figure 4. Energy profiles (mPWB1K/6-31+G(d,p), kcal·mol^{-1}, 357 K) for the transformations of ylide **13h** to dihydroazete **5a**.

Scheme 5. Cyclizations of 2-Azabutadienes 11b into Azetines 12b and Oxazine 4c



The difference in free energy of the diastereomers is 3.6 kcal·mol^{-1}. In fact, only one stereoisomer of dihydroazete **12b–d** was detected in all tested reactions (Table 2). Unexpectedly, the barriers for 1,5-cyclization of azadienes *E,Z*- and *Z,Z*-**11b** with C=C bond in *Z* configuration exceeded 34 kcal·mol^{-1} (Figure 5) that is by ~10 kcal·mol^{-1} higher than for cyclization of 4,4-diphenyl-substituted azadiene **3a** (Scheme 3). It is worthy of notice that the competitive 1,6-cyclization of *E,Z*-and *E,E*-isomers of **11b** on amide oxygen to give 2*H*-1,4-oxazine **4c** is both kinetically ($\Delta G^{\ddagger}$ 24.1 kcal·mol^{-1} for 1,4-cyclization vs. 25.2 kcal·mol^{-1} for 1,6-cyclization) and thermodynamically (azetine (*RS,SR*)-**12b** by 6 kcal·mol^{-1} more stable than oxazine **4c**) unfavorable process.

The significant increase in activation barrier for 1,4-cyclization of azadienes *E,Z*-**11b**, *Z,Z*-**11b** with *Z* configuration of C=C bond into dihydroazete **12b** can serve as the prerequisite for its transformation into indole, as the orientation of phenyl substituent at C^4 in principle allows the 1,5-cyclization to occur. However, after heating of *o*-xylene solution of azadiene *Z*-**11b** at 130 °C for several hours no signals of corresponding indole was found in ^{1}H NMR spectrum of the reaction mixture. After prolonged refluxing of solution only tarring was observed. We supposed, that the presence of the second substituent at atom C^4 of azadiene, which decreases the conjugation of the benzene ring with C=C bond is important for the formation of indole system. To check this assumption we addressed the 4,4-disubstituted 2-azabuta-1,3-diene **15** (Scheme 6), which is formed as byproduct along with 1,3-oxazine **14** in the known $Rh_2(OAc)_4$-catalyzed reaction of azirine **1e** with diazo compound **2b** (CH_2Cl_2, 40 °C).[26] Because the compound **15** cannot be separated from **14** by crystallization or by chromatography we heated at 103 °C the chromatographically pure 1:12 mixture of **14** and **15** in *α,α,α*-trifluorotoluene. In ^{1}H NMR spectrum of the reaction mixture a singlet signal at 6.01 ppm characteristic of the methine proton of indole **6k** was observed. It was found that in order to increase the yield of indole **6k** it is expedient to carry out the synthesis of the indole **6k** from azirine **1e** in refluxing *α,α,α*-trifluorotoluene without isolation of the mixture of oxazine **14** and azadiene **15**. This procedure gave indole **6k** in 12% yield. This result confirms that 1,5-cyclization of 1,1-diacceptor-substituted 4-phenyl-2-azabuta-1,3-dienes requires a presence of the second substituent at C^4.

From the computational and experimental results follow that 1,4-electrocyclization of 1,1-diacceptor-substituted 2-azabutadienes is kinetically and thermodynamically favorable for substrates with *cis*-oriented aryl/alkyl substituents at atoms C^3 and C^4. *Z*-Phenyl substituent at disubstituted atom C^4 changes the cyclization type, and in this case 1,5-cyclization of 2-azadiene into indole occurs with the lowest activation barrier. 1,6-Cyclization of 2-azabutadiene onto carbonyl of ester[10] or amide function is unfavorable both on kinetic and thermodynamic reasons. Finally, 1,6-cyclization of 2-azabutadiene onto *Z*-phenyl substituent is a high-barrier process and can occur when there are no structural prerequisites for 1,4- and 1,5-cyclizations.

It should be noted that in all tested reactions of 2-azabuta-1,4-dienes **3**, **11**, **15**, the competition between 1,4-, 1,5-, and 1,6-cyclization was not observed. In all cases the reactions

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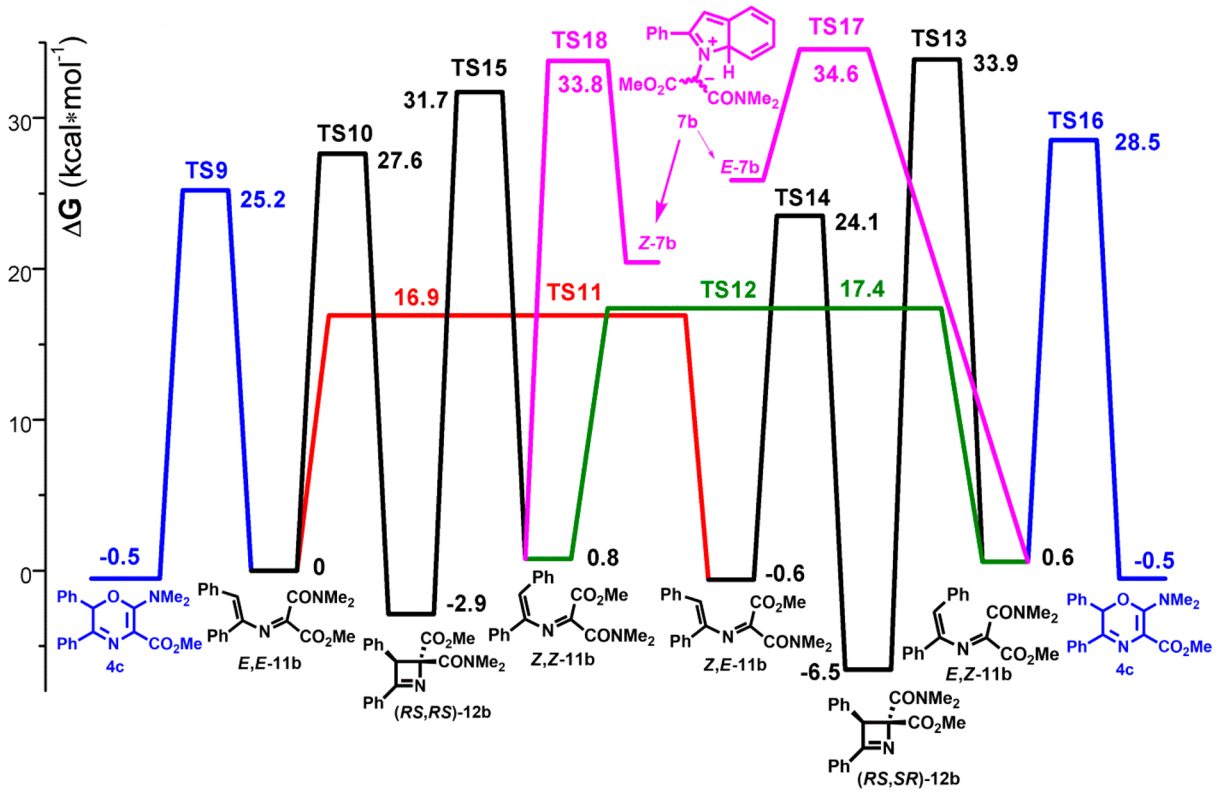
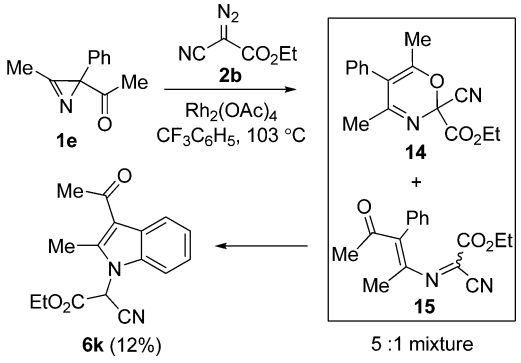


Figure 5. Energy profiles (mPWB1K/6-31+G(d,p), kcal·mol^{-1}, 357 K) for the transformations of 2-azabutadienes **11b** to dihydroazetes **12b**, 2*H*-1,4-oxazine **4c**, and indolium ylides **7b**.

Scheme 6. Synthesis of Indole 6k from Azirine 1e



proceed selectively, and the change of the cyclization type is controlled by substituents C^1 and C^4 as follows:

(a) Two geminal phenyl groups at C^4 provide smooth proceeding of 1,5-cyclization of 1,1-diacceptor-substituted 2-azabutadienes into indoles via pseudopericyclic mechanism with 7a*H*-indolium ylides as intermediates. The increase in electron-withdrawing ability of C^1-substituents accelerates indole formation.

(b) (*Z*)-4-Monophenyl-subsituted 2-azadienes do not produce indoles by this reaction due to extremely high activation barrier, which can be rationalized in terms of increased conjugation between (*Z*)-4-phenyl-substituent and C^3═C^4 double bond. The introduction of the second substituent at C^4 causes the breaking of the conjugation due to the violation of coplanarity of these fragments, and 1,5-cycization into indole becomes possible.

(c) (*Z*)-4-Monophenyl-subsituted 2-azadienes also do not undergo 1,4-electrocyclyzation into dihydroazetes even with two strong electron-withdrawing groups at C^1. However, this reaction strongly accelerates on going from *Z* isomer (across C═C bond) to *E* isomer. 1,4-Cyclization of 2-azadienes is a reversible process, and the increase of electron-withdrawing ability of C^1-substituents shifts an equilibrium toward dihydroazete.

(d) 1,6-Electrocyclization of 2-azadienes irrespective of the nature of C^1- and C^4-substituents cannot involve ester or amide carbonyl groups due to unfavorable both kinetic and thermodynamic factors, but can occur onto aromatic substituent at C^4 like benzene ring of fluorene system at elevated temperatures.

■ CONCLUSION

In conclusion, 2-azabuta-1,3-dienes readily prepared from 2,2-diphenyl-2*H*-azirines and *α*-diazocarbonyl compounds under $Rh_2(OAc)_4$-catalysis undergo thermal cyclization into indoles. The reaction proceeds via pseudopericyclic 1,5-electrocyclization into 7a*H*-indolium ylide followed by prototropic shift and provides indoles in good yields for 1,1-diacceptor-substituted 2-azabutadienes. The increase in electron-withdrawing ability of C^1-substituents decreases the activation barriers for the 7a*H*-indolium ylide formation. According to quantum-chemical calculations (DFT mPWB1K/6-31+G(d,p)) barrier for 1,5-cyclization of di(methoxycarbonyl)substituted 3,4,4-triphenyl-2-azabuta-1,3-diene is only 24.4 kcal·mol^{-1}. 2-(2,3-Diphenyl-/2-methyl-3-phenylindolyl)cyanoacetic and 2-(2-methyl-3-phenylindolyl)malonic and −3,3,3-trifluoropropionic acid esters can be prepared in good yields from diazo compounds and 2,2-diphenyl-2*H*-azirines without isolation of intermediate aza-

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diene. 2-Monophenyl-subsituted 2*H*-azirines do not produce indoles by this reaction due to the unfavorable *E* configuration of C=C bond of intermediate 2-azabutadiene. However, this configuration of the double bond is favorable for 1,4-cyclization to 2,3-dihydroazetes. At the same time, 1,6-electrocyclization onto *Z*-oriented phenyl substituent at C^4 of 2-azabutadiene fragment to give isoquinoline derivatives can occur at elevated temperatures. This type of cyclization is characteristic of the 2,2′-biphenylene substitution at C^4 in electron-poor 2-azadienes.

EXPERIMENTAL SECTION

General Experimental Details. 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 $CDCl_3$ and ^{1}H (400 MHz) and ^{13}C (100 MHz) NMR spectra were measured in $CDCl_3$ or C_6D_6. Chemical shifts (δ) are reported in ppm downfield from tetramethylsilane. IR spectra were recorded for tablets in KBr. Single crystal X-ray data for **6a** and **12d** were collected at a temperatures of 120 K and 100 K, respectively, using monochromated Mo Kα radiation. The structures were solved by direct method and refined by full-matrix least-squares on F^2 for all data using Olex2[27] and SHELXTL software.[28] Crystallographic data for the structures have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication CCDC-999525 (**6a**) and CCDC-998320 (**12d**). Compounds **1a**,[10] **1b**,[29] **1c**,[30] **1d**,[31] **1e**,[32] **2a**,[33] **2b**,[34] **2c**,[35] **2d**,[36] **2e**,[37] **2f**,[38] **2g**,[39] **2h**,[40] **2i** and **2j**[41] were prepared by the reported procedures.

General Procedure for the Catalytic Reaction of 2*H*-Azirines 1 with Diazocompounds 2. *Method A.* A solution of azirine **1a,b** (1 equiv) and diazo compound **2a−c,h** (1.5−2.5 equiv) in anhydrous 1,2-dichloroethane (DCE) was heated to reflux under argon atmosphere, and then $Rh_2(OAc)_4$ (5 mol %) was added in one portion. The mixture was stirred under reflux until evolution of nitrogen had ceased. Evaporation of the solvent under a vacuum and purification of the residue by chromatography on silica afforded the compound **3a−c,f−h**.

Method B. A solution of diazo compound **2b,c−e,g,i,j** (1.25−6 equiv) in anhydrous DCE under argon atmosphere was added dropwise with a syringe to a stirred solution of azirine **1a,c−e** (1 equiv) and $Rh_2(OAc)_4$ (5 mol %) in anhydrous DCE under heating until azirine was completely consumed (TLC analysis). Evaporation of the solvent under a vacuum and purification of the residue by chromatography on silica afforded the compounds **3d,e**, **4b**, **11a−c,e−g**, **12b−d**, **17**.

Dimethyl 2-[(1,2,2-triphenylvinyl)imino]malonate (3a). According to method A, a solution of azirine **1a** (30 mg, 0.112 mmol) and diazo compound **2a** (45 mg, 0.29 mmol) were reacted in DCE (0.5 mL) under reflux (5 min). Column chromatography (petroleum ether−EtOAc 6:1) followed by recrystallization gave compound **3a** (32 mg, 72%) as orange solid: mp 111−113 °C (hexane−Et_2O); ^{1}H NMR (400 MHz; $CDCl_3$), δ 3.39 (s, 3H), 3.88 (s, 3H), 7.02−7.30 (m, 15H); ^{13}C NMR (75 MHz; $CDCl_3$) δ 52.2, 53.3, 127.1, 127.5, 127.7, 127.8, 127.9, 128.0, 130.9, 131.5 (2C), 135.2, 137.6, 139.9, 140.9, 142.7, 151.9, 162.3 (2C); HRMS−ESI $[M + H]^+$ calcd for $C_{25}H_{22}NO_4^+$, 400.1543, found 400.1537.

Ethyl 2-cyano-2-(1,2,2-triphenylvinylimino)acetate (3b). According to method A, azirine **1a** (40 mg, 0.15 mmol) and diazo compound **2b** (42 mg, 0.3 mmol) were reacted in DCE (0.5 mL) at 40 °C (13 min). Column chromatography (petroleum ether−EtOAc 6:1) gave compound **3b** (43 mg, 76%) as orange oil which upon standing at rt slowly transforms to indole **6b**: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.36 (t, J = 7.2 Hz, 3H), 4.39 (q, J = 7.2 Hz, 2H), 7.07−7.43 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 63.3, 109.7, 127.4, 127.8, 128.2, 128.6, 128.8, 129.0, 129.2, 130.7, 131.5, 132.5, 136.5, 139.4, 140.2, 144.0, 146.3, 160.4; HRMS−ESI $[M + H]^+$ calcd for $C_{25}H_{21}N_2O_2^+$, 381.1598, found 381.1604.

Ethyl 3,3,3-trifluoro-2-(1,2,2-triphenylvinylimino)-propanoate (3c). According to method A, azirine **1a** (51 mg, 0.19 mmol) and diazo compound **2c** (53 mg, 0.29 mmol) were reacted in DCE (0.5 mL) under reflux (5 min). Column chromatography (benzene−EtOAc 400:1) followed by recrystallization gave compound **3c** (72 mg, 90%) as orange solid: mp 101−102 °C (hexane−Et_2O); R_f = 0.56 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.14 (t, J = 7.1 Hz, 3H), 3.92 (q, J = 7.1 Hz, 2H), 7.05−7.26 (m, 12H), 7.30−7.42 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.6, 62.5, 118.5 (q, J = 278.3 Hz), 122.7, 127.2, 127.7, 127.8, 127.9, 128.0, 130.6, 131.1, 131.4, 133.3, 137.1, 139.7, 140.7, 141.7, 149.2 (q, J = 36.7 Hz), 158.8; HRMS−ESI $[M + Na]^+$ calcd for $C_{25}H_{20}F_3NNaO_2^+$ 446.1338, found 446.1341.

Methyl 3-(dimethylamino)-3-oxo-2-(1,2,2-triphenylvinylimino)propanoate (3d). According to method B, azirine **1a** (17 mg, 0.063 mmol, 0.15 M solution in DCE) and diazo compound **2d** (114 mg, 0.66 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 1:1) followed by recrystallization gave compound **3d** (19 mg, 73%) as a 6.5:1 mixture of stereoisomers across C=N bond. Orange solid: mp 134−136 °C (hexane−Et_2O); R_f = 0.59 (50% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) (signals of the major isomer are indicated in bold font) δ **2.12** (s, 2.6H), **2.54** (s, 2.6H), 2.82 (s, 0.4H), 2.97 (s, 0.4H), 3.62 (s, 0.4H), **3.88** (s, 2.6H), 6.97−7.00 (m, 2H), 7.06−7.30 (m, 13H); ^{13}C NMR (100 MHz, $CDCl_3$) δ of major isomer 33.3, 36.3, 53.2, 126.8, 127.5 (2C), 127.6, 127.7, 127.8, 130.6, 131.4, 131.6, 134.0, 138.3, 140.07, 141.1, 142.6, 156.5, 162.6, 163.1; HRMS−ESI $[M + K]^+$ calcd for $C_{26}H_{24}KN_2O_3^+$ 451.1419, found 451.1427.

***N,N*-Dimethyl-2-phenyl-2-(1,2,2-triphenylvinylimino)-acetamide (3e).** According to method B, azirine **1a** (17 mg, 0.063 mmol, 0.15 M solution in DCE) and diazo compound **2e** (63 mg, 0.33 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 5:1) gave compound **3e** (19 mg, 66%) as orange oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.91 (s, 3H), 2.68 (s, 3H), 7.06−7.26 (m, 13H), 7.39−7.47 (m, 5H), 7.72−7.74 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.1, 36.5, 126.2, 126.7, 127.1, 127.3, 127.5 (2C), 127.6, 128.3, 128.8, 130.6, 131.1, 131.2, 131.9, 134.9, 139.3, 141.1, 142.1, 144.5, 163.8, 165.8; HRMS−ESI $[M + Na]^+$ calcd for $C_{30}H_{26}N_2NaO^+$ 453.1937, found 453.1929.

1-[Phenyl(fluorene-9-yliden)methylimino]-1-phenylpropane-2-one (3l). According to method A, 3-phenyl-2*H*,9′*H*-spiro-[azirine-1,9′-fluorene][42] (116 mg, 0.43 mmol) and 1-diazo-1-phenyl-propan-2-one **2h** (86 mg, 0.54 mmol) were reacted in DCE (0.5 mL) under reflux (1 min). Column chromatography (petroleum ether−EtOAc 10:1) followed by recrystallization gave compound **3l** (154 mg, 89%), which crystallizes from hexane as two different allotropic forms. Form 1: mp 118−119 °C (orange crystals, hexane); IR (KBr) 3060, 3030, 1705, 1620 cm^{-1}. Form 2: mp 125−126 °C (dark-red crystals, hexane); IR (KBr) 3055, 3025, 1700, 1625 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.62 (br s, 3H), 6.62 (br d, J = 7.0 Hz, 1H), 6.97 (m, J = 7.8 Hz, 1H), 7.05−7.70 (m, 13H), 7.81 (d, J = 7.8 Hz, 1H), 7.84−7.95 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.6 (br s), 119.4, 119.6, 121.4, 123.3, 125.3, 126.3, 126.7, 127.1, 127.2, 128.3, 128.4, 128.5, 128.8, 129.3, 130.9 (br s), 133.3, 137.4, 137.7, 137.7, 139.5, 139.6, 147.9, 166.0, 200.7; HRMS−ESI $[M + Na]^+$ calcd for $C_{29}H_{21}NONa^+$ 422.1515, found 422.1515.

1-(6-Methyl-2,2,3-triphenyl-2*H*-1,4-oxazin-5-yl)ethanone (4b) and 2,5,6-Trimethyl-2-(6-methyl-2,2,3-triphenyl-2*H*-1,4-oxazine-5-yl)-4*H*-1,3-dioxin-4-one (4b′). According to method B, azirine **1a** (116 mg, 0.5 mmol, 0.7 M solution in DCE) and 3-diazo-2,4-pentanedione **2g** (255 mg, 2.02 mmol, 2.5 M solution in DCE) were reacted at 60 °C. Column chromatography (petroleum ether−EtOAc 8:1) gave azirine **1a** (9 mg, 7%), oxazine **4b** (79 mg, 43%, 46% on consumed **1a**) and oxazine **4b′** (23 mg, 10%). Compound **4b**. Colorless solid: mp 165−170 °C (Et_2O, dec.); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.38 (s, 3H), 2.49 (s, 3H), 7.18 (t, J = 7.2 Hz, 2H), 7.24 (t, J = 7.2 Hz, 1H), 7.32 (s, 10H), 7.45 (d, J = 8.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 18.4, 28.2, 83.4, 127.6, 128.1, 128.3, 128.75, 128.85, 129.0, 129.1, 137.3, 140.2, 151.0, 154.9, 198.4; HRMS−ESI $[M + H]^+$

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calcd for $C_{25}H_{22}NO_2^+$ 368.1645, found 368.1648. Compound **4b′**. Yellowish solid: mp 145−146 °C; R_f = 0.33 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.21 (s, 3H), 1.73 (s, 3H), 1.92 (s, 3H), 2.16 (s, 3H), 7.07−7.42 (m, 15H); ^{13}C NMR (100 MHz $CDCl_3$) δ 10.1, 16.8, 17.0, 26.4, 82.3, 102.2, 103.8, 126.3, 127.5, 127.8, 127.99, 128.03, 128.3, 128.7, 128.8, 129.0, 129.3, 137.3, 140.3, 142.2, 144.1, 151.7, 162.4, 162.5; HRMS−ESI [M + H]$^+$ calcd for $C_{30}H_{28}NO_4^+$ 466.2013, found 466.2016.

Dimethyl 2-(2,3-diphenyl-1*H*-indol-1-yl)malonate (6a). A solution of azadiene **3a** (32 mg, 0.08 mmol) in anhydrous toluene (8 mL) was refluxed for 45 min under argon atmosphere. The solvent was removed under a vacuum and the residue was treated with hexane (0.5 mL) to give indole **6a** (26 mg, 81%) as colorless solid: mp 176−178 °C (Et_2O); R_f = 0.28 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.81 (s, 6H), 5.71 (s, 1H), 7.20−7.44 (m, 13H), 7.78 (d, J = 7.8 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 53.2, 60.7, 111.6, 117.1 119.8, 121.0, 123.0, 126.0, 128.0, 128.1, 128.7 (2C), 129.9, 130.9, 131.3, 134.4, 136.3, 137.3, 166.2; HRMS−ESI [M + H]$^+$ calcd for $C_{25}H_{22}NO_4^+$ 400.1543, found 400.1549. Anal. Calcd for $C_{25}H_{21}NO_4$: C, 75.17; H, 5.30; N, 3.51. Found: C, 74.98; H, 5.26; N, 3.48. Crystal data (CCDC-999525): $C_{25}H_{21}NO_4$, M 399.43 orthorhombic, space group *Pbca*, a = 15.8984(4), b = 12.9658(3), c = 19.5357(5) Å, U = 4027.0(2) Å^3, F(000) = 1680, Z = 8, D_c = 1.318 mg m^{-3}, μ = 0.089 mm^{-1}. 63105 reflections were collected yielding 5346 unique data (R_{merg} = 0.067). Final $wR_2(F^2)$ = 0.1109 for all data (355 refined parameters), conventional R_1 (F) = 0.0414 for 5539 reflections with $I \geq 2\sigma$, GOF = 1.060.

Ethyl 2-cyano-2-(2,3-diphenyl-1*H*-indol-1-yl)acetate (6b). *Synthesis from Azadiene **3b**.* A solution of azadiene **3b** (43 mg, 0.113 mmol) in $CDCl_3$ (0.5 mL) was kept at rt for 70 h (or refluxed in DCE for 20 min). Evaporation of the solvent under a vacuum affords compound **6b** quantitatively.

*Synthesis from Azirine **1a**.* A solution of azirine **1a** (40 mg, 0.15 mmol) and diazo compound **2b** (42 mg, 0.3 mmol) in anhydrous DCE (0.5 mL) was heated to 40 °C under argon atmosphere, and then $Rh_2(OAc)_4$ (3 mg, 0.007 mmol) was added in one portion. The mixture was stirred at 40 °C until evolution of nitrogen had ceased (13 min). The resulting solution was refluxed for 20 min and after evaporation of the solvent under a vacuum and purification of the residue by chromatography on silica (petroleum ether−EtOAc 6:1) indole **6b** (43 mg, 76%) was obtained as colorless viscous oil: R_f = 0.29 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.32 (t, J = 7.2 Hz, 3H), 4.37 (m, 2H), 5.93 (s, 1H), 7.24−7.51 (m, 13H), 7.82 (d, J = 7.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 13.9, 48.7, 64.2, 110.2, 112.7, 118.1, 120.5, 122.0, 123.7, 126.4, 128.3, 128.4, 129.1, 129.2, 129.8, 129.9, 131.1, 133.8, 135.6, 136.6, 162.8; HRMS−ESI [M + H]$^+$ calcd for $C_{25}H_{21}N_2O_2^+$ 381.1598, found 381.1603.

Ethyl 2-(2,3-diphenyl-1*H*-indol-1-yl)-3,3,3-trifluoropropanoate (6c). A solution of azadiene **3c** (17 mg, 0.04 mmol) in anhydrous *o*-xylene (6 mL) was refluxed for 40 min under argon atmosphere. The solvent was removed under a vacuum and the residue was purified by column chromatography on silica (petroleum ether−EtOAc 12:1) to give indole **6c** (11 mg, 65%) as viscous colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.24 (t, J = 7.1 Hz, 3H), 4.32 (m, 2H), 5.40 (q, J = 7.8 Hz, 1H), 7.17−7.50 (m, 13H), 7.79 (d, J = 7.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.9, 58.8 (q, J = 32.4 Hz), 62.9, 111.5 (q, J = 3.0 Hz), 117.9, 120.0, 121.4, 122.7 (q, J = 284.0 Hz), 123.2, 126.2, 128.2, 128.3, 128.9, 129.1, 129.8, 130.6, 131.6, 134.1, 135.7, 138.2, 163.7; HRMS−ESI [M + H]$^+$ calcd for $C_{25}H_{21}F_3NO_2^+$ 424.1519, found 424.1519.

Methyl 3-(dimethylamino)-2-(2,3-diphenyl-1*H*-indol-1-yl)-3-oxopropanoate (6d). A solution of azadiene **3d** (28 mg, 0.068 mmol) in anhydrous *o*-xylene (2 mL) was refluxed for 4 h under argon atmosphere. The solvent was removed under a vacuum and the residue was purified by column chromatography on silica (hexane−EtOAc 4:1) to give indole **6d** (18 mg, 64%) as colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.38 (s, 3H), 2.87 (s, 3H), 3.92 (s, 3H), 5.69 (s, 1H), 7.20−7.26 (m, 5H), 7.28−7.30 (m, 4H), 7.40−7.42 (m, 3H), 7.60−7.61 (m, 1H), 7.75−7.77 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 36.2, 36.4, 53.0, 61.7, 112.2, 116.9, 119.7, 121.0, 123.3, 126.0, 127.9, 128.2, 128.8, 128.9, 129.9, 130.9, 131.0, 134.4, 136.6, 136.9, 165.2, 168.0; HRMS−ESI [M + Na]$^+$ calcd for $C_{26}H_{24}N_2NaO_3^+$ 435.1679, found 435.1683.

Dimethyl 2-(2-methyl-3-phenyl-1*H*-indol-1-yl)malonate (6f). A solution of azirine **1b** (30 mg, 0.145 mmol) and diazo compound **2a** (43 mg, 0.27 mmol) in anhydrous DCE (0.5 mL) was heated to reflux under argon atmosphere, and then $Rh_2(OAc)_4$ (3 mg, 0.007 mmol) was added in one portion. The mixture was stirred under reflux until evolution of nitrogen had ceased (8 min). According to ^{1}H NMR spectrum of the reaction mixture dimethyl 2-[(1-methyl-2,2-diphenylvinyl)imino]malonate **3f** and indole **6f** was formed in 5.3:1 ratio. The resulting solution was diluted with anhydrous DCE (4 mL) and then refluxed for 1.5 h. After evaporation of the solvent under a vacuum and purification of the residue by chromatography on silica (petroleum ether−EtOAc 6:1) indole **6f** (37 mg, 76%) was obtained as viscous colorless oil. Compound **3f** (not isolated): ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.01 (s, 3H), 3.72 (s, 3H), 3.90 (s, 3H), 7.07 (d, J = 7.2 Hz, 2H), 7.12−7.39 (m, 8H). Compound **6f**: R_f = 0.44 (33% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.49 (s, 3H), 3.87 (s, 6H), 5.90 (s, 1H), 7.15−7.28 (m, 2H), 7.32−7.40 (m, 2H), 7.46−7.57 (m, 4H), 7.66 (d, J = 7.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.2, 53.3, 60.0, 110.0, 116.5, 119.0, 120.5, 121.9, 126.2, 127.9, 128.4, 129.9, 132.7, 135.0, 136.0, 166.2; HRMS−ESI [M + Na]$^+$ calcd for $C_{20}H_{19}NNaO_4^+$ 360.1206, found 360.1211.

Ethyl 2-cyano-2-(2-methyl-3-phenyl-1*H*-indol-1-yl)acetate (6g). A solution of azirine **1b** (30 mg, 0.145 mmol) and diazo compound **2b** (39 mg, 0.28 mmol) in anhydrous DCE (0.5 mL) was heated to 40 °C under argon atmosphere, and then $Rh_2(OAc)_4$ (3 mg, 0.007 mmol) was added in one portion. The mixture was stirred at 40 °C until evolution of nitrogen had ceased (5 min). The resulting solution was diluted with anhydrous DCE (4 mL) and then refluxed for 15 min. After evaporation of the solvent under a vacuum and purification of the residue by chromatography on silica (petroleum ether−EtOAc 7:1) indole **6g** (33 mg, 72%) was obtained as viscous colorless oil: R_f = 0.24 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.35 (t, J = 7.1 Hz, 3H), 2.53 (s, 3H), 4.40 (qq, J = 10.8, 7.1 Hz, 2H), 6.04 (s, 1H), 7.22 (t, J = 7.5 Hz, 1H), 7.31 (t, J = 7.5 Hz, 1H), 7.35−7.43 (m, 2H), 7.48−7.55 (m, 4H), 7.66 (d, J = 7.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 10.9, 14.0, 48.0, 64.3, 109.0, 112.7, 117.5, 119.6, 121.4, 122.7, 126.6, 128.3, 128.6, 129.8, 131.7, 134.3, 135.3, 162.7; HRMS−ESI [M + Na]$^+$ calcd for $C_{20}H_{18}N_2NaO_2^+$ 341.1260, found 341.1266.

Ethyl 3,3,3-trifluoro-2-(2-methyl-3-phenyl-1*H*-indol-1-yl)-propanoate (6h). A solution of azirine **1b** (34 mg, 0.164 mmol) and diazo compound **2c** (44 mg, 0.26 mmol) in anhydrous DCE (0.5 mL) was heated to reflux under argon atmosphere, and then $Rh_2(OAc)_4$ (3 mg, 0.007 mmol) was added in one portion. The mixture was stirred under reflux until evolution of nitrogen had ceased (3 min). Evaporation of the solvent under a vacuum gave crude ethyl 3,3,3-trifluoro-2-(1-methyl-2,2-triphenylvinylimino)propanoate **3h**. This material was dissolved in anhydrous toluene (5 mL) and then refluxed for 1 h. After evaporation of the solvent under a vacuum and purification of the residue by chromatography on silica (petroleum ether−EtOAc 12:1) indole **6h** (36 mg, 61%) was obtained as colorless solid: mp 92−93 °C (hexane). Compound **3h** (not isolated); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.24 (t, J = 7.1 Hz, 3H), 2.03 (s, 3H), 4.19 (q, J = 7.1 Hz, 2H), 7.02 (d, J = 7.3 Hz, 2H), 7.12−7.39 (m, 8H). Compound **6h**: R_f = 0.39 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.25 (br t, J = 7.0 Hz, 3H), 2.51 (s, 3H), 4.28−4.43 (br m, 2H), 5.52 (br s, 1H), 7.16−7.29 (m, 2H), 7.34−7.42 (m, 2H), 7.48−7.57 (m, 4H), 7.65 (d, J = 7.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 11.0, 13.9, 58.5 (q, J = 32.5 Hz), 63.0, 110.3, 117.1, 119.2, 120.9, 122.4, 122.8 (q, J = 283.7 Hz), 126.5, 128.3, 128.5, 130.0, 132.8, 134.7, 135.7, 163.5 HRMS−ESI [M + Na]$^+$ calcd for $C_{20}H_{18}F_3NNaO_2^+$ 384.1182, found 384.1184.

Ethyl 2-(2,3-diphenyl-1*H*-indol-1-yl)-3-oxobutanoate (6i). A solution of oxazine **4a** (19 mg, 0.048 mmol) in anhydrous toluene (2 mL) was refluxed for 10 h under argon atmosphere. The solvent was removed in vacuum and the residue was purified by column chromatography on silica (petroleum ether−EtOAc 10:1) to give

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indole **6i** (14 mg, 74%) as colorless viscous oil: R_f = 0.51 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.12 (t, J = 7.2 Hz, 3H), 1.76 (s, 3H), 4.05−4.27 (m, 2H), 7.19−7.42 (m, 13H), 7.83 (d, J = 7.6 Hz, 1H), 12.70 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 18.0, 61.1, 102.9, 110.2, 116.3, 119.7, 120.8, 122.7, 125.8, 127.6, 127.9, 128.1, 128.2, 130.0, 130.5, 131.9, 134.9, 138.1, 138.2, 170.7, 176.7; HRMS−ESI $[M + H]^+$ calcd for $C_{26}H_{24}NO_3^+$ 398.1751, found 398.1754.

3-(2,3-Diphenyl-1*H*-indol-1-yl)pentane-2,4-dione (6j). A solution of oxazine **4b** (25 mg, 0.068 mmol) in anhydrous *o*-xylene (3 mL) was refluxed for 3 h under argon atmosphere. The solvent was removed in a vacuum and the residue was treated with hexane (0.5 mL) to give indole **6j** (20 mg, 80%) as colorless solid: mp 145−175 °C (EtOAc, dec.); R_f = 0.49 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.85 (s, 6H), 7.17−7.43 (m, 13H), 7.87 (d, J = 7.6 Hz, 1H), 16.05 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.8, 110.1, 113.2, 117.2, 120.0, 121.2, 123.3, 126.1, 127.7, 128.1, 128.3, 128.4, 130.0, 130.6, 131.4, 134.6, 137.6, 137.7, 192.0; HRMS (ESI) calcd for $C_{25}H_{22}NO_2$ $[M + H]^+$ 368.1645, found 368.1648.

Methyl 1-phenyl-2-azafluoranthene-3-carboxylate (9a). Compound **3k** (100 mg, 0.25 mmol) in anhydrous *o*-xylene (30 mL) was placed into a screw caped ampule and heated under argon atmosphere at 170 °C for 4 h. The solvent was removed under a vacuum and the residue was purified by column chromatography on silica (petroleum ether−EtOAc 30:1) to give azafluoranthene **9a** (16 mg, 19%) as yellow solid: mp 156−157 °C (hexane−Et_2O); R_f = 0.29 (20% EtOAc/hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.12 (s, 3H), 7.21−7.28 (m, 1H), 7.38−7.43 (m, 1H), 7.58−7.60 (m, 3H), 7.73−7.78 (m, 2H), 7.90−7.94 (m, 3H), 8.07 (d, J = 6.9 Hz, 1H), 8.75 (d, J = 8.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 53.0 (CH_3O), 121.9, 123.8, 123.9, 124.5, 126.4, 128.1, 128.7, 128.9, 129.1, 129.9, 130.3, 131.0, 136.5, 137.6, 138.0, 139.0, 139.8, 145.5, 148.7, 165.9; HRMS−ESI $[M + H]^+$ calcd for $C_{23}H_{16}NO_2^+$ 338.1176, found 338.1193.

Methyl 1,3-diphenyl-2-azafluoranthene (9b). Compound **3l** (45 mg, 0.11 mmol) in anhydrous *o*-xylene (10 mL) was placed into a screw caped ampule and heated under argon atmosphere at 170 °C for 15 h. The solvent was removed under a vacuum and the residue was purified by column chromatography on silica (benzene−EtOAc 300:1) to give azafluoranthene **9b** (18 mg, 46%) as yellow solid and 9*H*-fluoren-9-one (2 mg, 10%). Compound **9b**: mp 185−187 °C (Et_2O); R_f = 0.47 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28 (dd, J = 7.4 Hz, J = 0.9 Hz, 1H), 7.41 (dd, J = 7.4 Hz, J = 0.9 Hz, 1H), 7.52−7.64 (m, 6H), 7.72 (m, 1H), 7.83 (d, J = 7.8 Hz, 1H), 7.93−8.04 (m, 5H), 8.09−8.17 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 121.7, 123.0 (2C), 123.8, 126.5, 126.6, 127.8 (2C), 128.4, 128.5, 128.7, 128.8, 128.9, 129.9, 130.6, 136.6, 138.0, 138.3, 139.0, 139.2, 140.1, 149.3, 158.7; HRMS−ESI $[M + H]^+$ calcd for $C_{27}H_{18}N^+$ 356.1434, found 356.1429.

***N*,*N*-Dimethylamino-2-phenyl-2-{[(*E*)-1,2-diphenylvinyl]-imino}acetamide (*E*-11a).** According to method B, azirine **1c** (30 mg, 0.15 mmol, 0.15 M solution in DCE) and diazo compound **2e** (95 mg, 0.5 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 10:1) gave compound *E*-**11a** (38 mg, 67%) as yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.59 (s, 3H), 3.02 (s, 3H), 6.25 (s, 1H), 7.09−7.18 (m, 5H), 7.29−7.32 (m, 3H), 7.44−7.51 (m, 5H), 7.88−7.91 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.5, 37.4, 114.5, 126.2, 127.8, 128.0, 128.1, 128.3, 128.8, 129.1, 129.2, 131.4, 134.4, 136.6, 148.9, 160.2, 166.0; HRMS−ESI $[M + Na]^+$ calcd for $C_{24}H_{22}N_2NaO^+$ 377.1624, found 377.1619.

Methyl 3-(dimethylamino)-2-((*Z*)-1,2-diphenylvinylimino)-3-oxopropanoate (*Z*-11b), Methyl 3-(dimethylamino)-2-((*E*)-1,2-diphenylvinylimino)-3-oxopropanoate (*E*-11b) and Methyl (2*RS*,3*SR*)-2-(dimethylcarbamoyl)-3,4-diphenyl-2,3-dihydroazete-2-carboxylate (12b). According to method B, azirine **1c** (30 mg, 0.15 mmol, 0.15 M solution in DCE) and diazo compound **2d** (159 mg, 0.9 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (CH_2Cl_2−EtOAc 1:1) gave compound *Z*-**11b** (7 mg, 14%) as a 6.5:1 mixture of stereoisomers across C=N bond and an equilibrium mixture of compounds *E*-**11b** and **12b** (36 mg, 1:1.5, 71%). Compound *Z*-**11b**. Orange oil: R_f = 0.53 (50% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) (signals of the major isomer are indicated in bold font) δ **2.25** (s, 2.6H), **2.62** c (2.6H), 3.12 (s, 0.4H), 3.18 (s, 0.4H), 3.50 (s, 0.4H), **4.00** (s, 2.6H), 6.32 (s, 1H), 7.32−7.45 (m, 10H); ^{13}C NMR (100 MHz, $CDCl_3$) δ of major isomer 33.6, 36.2, 53.5, 117.1, 126.9, 127.1, 128.3, 128.4, 128.5, 129.8, 135.8, 137.7, 145.6, 156.7, 162.2, 162.7; HRMS−ESI $[M + Na]^+$ calcd for $C_{20}H_{20}N_2NaO_3^+$ 359.1366, found 359.1379. A mixture of compounds *E*-**11b** and **12b**. Yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) (nonaromatic signals of *E*-**11b** are indicated in bold font) δ **2.66** (s, 1.9H), **2.76** (s, 1.9H), 3.05 (s, 3H), 3.24 (s, 3H), 3.28 (s, 3H), **3.95** (s, 1.9H), 5.77 (s, 1H), **6.60** (s, 0.65H), 6.98−7.02 (m, 1.68H), 7.13−7.15 (m, 2.54H), 7.22−7.55 (m, 10H), 7.74−7.77 (m, 2H); HRMS−ESI $[M + H]^+$ calcd for $C_{20}H_{21}N_2O_3^+$ 337.1547, found 337.1547. Compound *E*-**11b**: ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.6, 37.1, 53.4, 123.3, 127.8, 128.3, 128.7, 129.0, 134.9, 135.2, 147.0, 152.0, 162.8, 163.5, 4 unseparated aromatic carbons are not described. Compound **12b**: ^{13}C NMR (100 MHz, $CDCl_3$) δ 36.2, 37.2, 52.0, 55.4, 79.0, 126.8, 128.3, 128.6, 128.7, 127.5, 129.4, 129.5, 131.0, 132.5, 133.6, 166.3, 167.7, 190.4.

Methyl 3-(*N*-methyl-*N*-methoxyamino)-2-((*E*)-1,2-diphenylvinylimino)-3-oxopropanoate (*E*-11c) and Methyl (2*RS*,3*SR*)-2-(*N*-methyl-*N*-methoxycarbamoyl)-3,4-diphenyl-2,3-dihydroazete-2-carboxylate (12c). According to method B, azirine **1c** (30 mg, 0.15 mmol, 0.15 M solution in DCE) and diazo compound **2i** (116 mg, 0.62 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 6:1) gave compound **12c** (17 mg, 31%) and unseparated mixture of compounds *E*-**11c** and **12c** (4 mg, 6%). According to ^{1}H NMR spectrum of the reaction mixture the compound *E*-**11c** was formed in 5% yield. Azadiene *E*-**11c** cannot be separated from dihydroazete **12c** as it rather quickly cyclizes to give equilibrium mixture *E*-**11c**/**12c** in 1:7 ratio. Dihydroazete **12c** is stable at rt but produces an equilibrium mixture after reflux in toluene for 1 h. Compound *E*-**11c** (not separated from **12c**): ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.11 (s, 3H), 3.67 (s, 3H), 3.93 (s, 3H), 6.42 (s, 1H), unseparated aromatic protons are not described. Compound **12c**. Colorless oil; R_f = 0.57 (50% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.26 (s, 3H), 3.31 (s, 3H), 3.93 (s, 3H), 5.73 (s, 1H), 7.20−7.23 (m, 2H), 7.27−7.32 (s, 3H), 7.39−7.43 (s, 2H), 7.49−7.54 (m, 1H), 7.78 (d, J = 7.3 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 32.9, 51.7, 54.6, 62.1, 77.8, 126.8, 127.8, 128.3, 128.6, 129.0, 131.1, 132.4, 133.4, 166.9, 167.7, 190.7; HRMS−ESI $[M + Na]^+$ calcd for $C_{20}H_{20}N_2NaO_4^+$ 375.1315, found 375.1318.

Methyl (2*RS*,3*SR*)-2-(1*H*-indole-1-carbonyl)-3,4-diphenyl-2,3-dihydroazete-2-carboxylate (12d). According to method B, azirine **1c** (20 mg, 0.1 mmol, 0.15 M solution in DCE) and diazo compound **2j** (50 mg, 0.2 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 30:1) followed by crystallization gave compound **12d** (18 mg, 44%) as a colorless solid. Carrying out of the reaction in $CHCl_3$ under reflux affords dihydroazete **12d** in 52% yield: mp 52−54 °C (hexane−Et_2O); R_f = 0.35 (20% EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.16 (s, 3H), 5.79 (s, 1H), 6.64 (d, J = 3.8 Hz, 1H), 7.21−7.54 (m, 11H), 7.72−7.75 (m, 2H), 8.09 (d, J = 3.8 Hz, 1H), 8.48−8.51 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 52.5, 55.5, 79.5, 110.3, 116.7, 120.8, 124.4, 125.2, 126.1, 127.0, 128.2, 128.6, 128.7, 129.1, 130.5, 130.7, 132.88, 132.94, 136.0, 164.8, 166.9, 190.8; HRMS−ESI $[M + Na]^+$ calcd for $C_{26}H_{20}N_2NaO_3^+$ 431.1366, found 431.1355. Crystal data (CCDC-998320): $C_{26}H_{20}N_2O_3$, M 408.44, monoclinic, space group $P21/a$: a = 12.5026(4), b = 13.2431(3), c = 12.5514(4) Å; α = 90.00, β = 99.250(3), γ = 90.00°; U = 2051.14(10) Å^3; Z = 4; d = 1.323 mg/mm^3, μ(Mo Kα) = 0.087 mm^{-1}, T 100(2)K, 10036 reflections measured, 4623 unique (R_{int} = 0.0239) were used in all calculations. The final was 0.0401 (3799 > 2σ(I)) and wR_2 was 0.0939 (all data).

***N*,*N*-Dimethyl-2-phenyl-2-(1-phenylvinylimino)acetamide (11e).** According to method B, azirine **1d** (30 mg, 0.25 mmol, 0.15 M solution in DCE) and diazo compound **2e** (95 mg, 0.5 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 2:1) gave compound **11e** (29 mg, 62%) as orange oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.62 (s, 3H), 3.02 (s, 3H),

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4.74 (s, 1H), 5.08 (s, 1H), 7.31−7.38 (m, 4H), 7.48−7.50 (m, 2H), 7.66−7.68 (m, 2H), 7.92−7.95 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 33.6, 37.4, 96.8, 125.5, 128.0, 128.4, 128.8, 129.7, 131.6, 134.4, 137.2, 153.7, 161.2, 165.9; HRMS−ESI $[M + Na]^+$ calcd for $C_{18}H_{18}N_2NaO^+$ 301.1311, found 301.1329.

Methyl 3-(dimethylamino)-3-oxo-2-(1-phenylvinylimino)-propanoate (11f). According to method B, azirine **1d** (38 mg, 0.33 mmol, 0.15 M solution in DCE) and diazo compound **2d** (100 mg, 0.58 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (CH_2Cl_2−EtOAc 8:1) gave compound **11f** (40 mg, 47%) as a 4.3:1 mixture of stereoisomers across C=N bond. Azadiene **11f** is unstable in $CDCl_3$ solution. Orange oil: ^{1}H NMR (400 MHz, C_6D_6) (signals of the major isomer are indicated in bold font) δ **2.14** (s, 3H), **2.48** (s, 3H), 2.56 (s, 0.7H), 2.68 (s, 0.7H), 3.22 (s, 0.7H), **3.37** (s, 3H), 4.52 (s, 0.22H), 4.79 (s, 0.22H), **4.88** (s, 1H), **4.90** (s, 1H), 7.04−7.11 (m, 3.8H, of both isomers), 7.52 (d, J = 6.8 Hz, 0.45H), **7.59** (d, J = 6.8 Hz, 2H); ^{13}C NMR (100 MHz, C_6D_6) δ **33.2**, 34.8, **36.3**, 37.4, 51.7, **52.5**, 95.0, **98.0**, **125.9**, 126.2, 128.6, 128.7, **128.8**, **128.9**, 135.6, **136.4**, **153.2**, **154.3**, 154.7, 155.1, 163.0, **163.1**, **163.4**, 163.8; HRMS−ESI $[M + Na]^+$ calcd for $C_{14}H_{16}N_2NaO_3^+$ 283.1053, found 283.1043.

Methyl 3-(1*H*-indol-1-yl)-3-oxo-2-(1-phenylvinylimino)-propanoate (11g) and Dimethyl 2,3-di(1*H*-indole-1-carbonyl)-5-phenyl-3,4-dihydro-2*H*-pyrrole-2,3-dicarboxylate (11g′). According to method B, azirine **1d** (25 mg, 0.21 mmol, 0.15 M solution in DCE) and diazo compound **2j** (107 mg, 0.44 mmol, 0.3 M solution in DCE) were reacted under reflux. Column chromatography (petroleum ether−EtOAc 2:1) followed by crystallization gave compound **11g** (27 mg, 39%) as a 3.2:1 mixture of stereoisomers across C=N bond and compound **11g′** (21 mg, 18%) as diastereomeric mixture in 1:1 ratio. Compound **11g**. Orange oil: ^{1}H NMR (400 MHz, $CDCl_3$) (signals of nonaromatic protons of the major isomer are indicated in bold font) δ 3.85 (s, 0.9H), **4.00** (s, 3H), 4.70 (s, J = 0.8 Hz, 0.3H), **4.72** (s, 1H), **4.92** (s, 1H), 5.05 (d, J = 0.8 Hz, 0.3H), **6.50** (d, J = 2.8 Hz, 1H), 6.71 (d, J = 3.8 Hz, 0.3H), **6.84** (d, J = 2.8 Hz, 1H), 7.30−7.63 (m, 14H), 8.01 (d, J = 3.8 Hz, 0.3H), 8.07 (d, 0.6H), 8.46 (d, J = 8.1 Hz, 1H), 8.52 (d, J = 8.2 Hz, 0.3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 52.7, 53.8, 96.7, 99.2, 110.7, 111.2, 116.7, 117.0, 121.0, 121.1, 124.3, 124.9, 125.5, 125.7, 125.8, 126.6, 128.5, 128.6, 129.0, 129.1, 130.6, 130.7, 134.8, 134.9, 135.5, 136.0, 151.4, 152.9, 153.0, 153.9, 161.5, 161.5, 161.7; HRMS−ESI $[M + Na]^+$ calcd for $C_{20}H_{16}N_2NaO_3^+$ 355.1053, found 355.1053.

Compound **11g′** (diastereomeric mixture). Beige solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.71 (s, 3H), 3.74 (s, 3H), 3.80 (s, 3H), 3.82 (s, 3H), 3.94 (d, J =17.2 Hz, 1H), 3.95 and 4.16 (AB-q, J = 16.6 Hz, 1H), 4.30 (d, J = 17.2 Hz, 1H), 6.63 (m, 4H), 7.30−7.62 (m, 20H), 7.93−7.96 (m, 4H), 8.30−8.38 (m, 2H), 8.45−8.50 (m, 1H), 8.56−8.60 (m, 2H), 8.68 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 46.3 (2C), 53.4, 53.7, 53.8, 53.9, 70.8 (2C), 94.8, 97.3, 108.6, 108.8, 109.8, 109.9, 117.0, 117.1, 117.2, 117.4, 120.46, 120.51, 120.7, 120.8, 123.98, 124.0 (2C), 124.1, 124.2, 124.4, 124.8, 124.9, 125.2, 125.7, 125.37, 125.42, 125.5, 128.0, 128.3, 128.4, 128.70, 128.72, 129.0, 129.6, 129.8, 130.2, 130.3, 132.2, 132.3, 132.4, 132.5, 136.8 (2C), 136.9, 137.1, 137.2, 166.7, 167.5, 170.2, 170.4, 171.2, 174.4; HRMS−ESI $[M + Na]^+$ calcd for $C_{32}H_{25}N_3NaO_6^+$ 570.1636, found 570.1641.

Ethyl 2-(3-acetyl-2-methyl-1*H*-indol-1-yl)-2-cyanoacetate (6k). According to method B, azirine **1e** (86 mg, 0.5 mmol) in anhydrous TFT (5 mL) and diazo compound **2b** (70 mg, 0.5 mmol) were reacted under reflux. Column chromatography (hexane−EtOAc 5:1) gave compound **6k** (18 mg, 12% on consumed azirine) and oxazine **14** (87 mg, 56% on consumed azirine). According to ^{1}H NMR spectrum of the reaction mixture the conversion of azirine **1e** was 82%. Compound **6k**. Yellowish oil: IR (KBr) 3059, 2990, 2947, 2925, 2853, 2257, 1755, 1643 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.32 (t, J = 7.1 Hz, 3H), 2.73 (s, 3H), 2.83 (s, 3H), 4.35−4.40 (m, 2H), 6.10 (s, 1H), 7.34−7.42 (m, 3H), 8.01−8.03 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 12.5, 13.9, 31.9, 47.2, 64.8, 109.5, 111.9, 116.6, 121.3, 123.2, 123.4, 126.5, 134.9, 142.9, 161.8, 194.9; HRMS−ESI $[M + H]^+$ calcd for $C_{16}H_{17}N_2O_3^+$ 285.1234, found 285.1243.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Figures S1−S3 with energy profiles for the transformations of azadienes **11i−k**, ^{1}H and ^{13}C NMR spectra for all new compounds, and crystallographic data for **6a** and **12d** (CIF format). Figures with tube representation of the calculated molecules. Computation details: energies of the reactants, transition states, their Cartesian coordinates. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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