Reactions of diazo ketones with activated unsaturated compounds in the presence of gallium trichloride*

R. A. Novikov, Yu. V. Tomilov, and O. M. Nefedov*

N. D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences,
47 Leninsky prosp., 119991 Moscow, Russian Federation.
Fax: +7 (499) 135 6390. E-mail: tom@ioc.ac.ru

Diazoacetone reacts with methyl acrylate in the presence of anhydrous $GaCl_3$ to give isomeric methyl 2-acetylcyclopropanecarboxylates rather than pyrazolines obtained from diazo esters or by noncatalytic reactions. In a similar reaction, diazoacetophenone yields methyl 2-benzoylcyclopropanecarboxylates, benzoylmethyl acrylate, and benzoylmethyl 2-benzoylcyclopropanecarboxylate *via* partial transesterification. Addition of an equimolar amount of $GaCl_3$ to diazoacetone in the system CH_2Cl_2—HCl—H_2O unexpectedly produces 4,5-dimethylfuran-3(2*H*)-one and 1,1′-oxybis(propan-2-one).

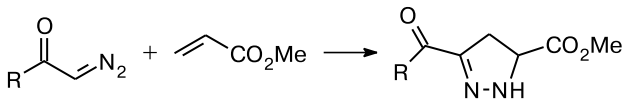
Key words: diazoacetone, diazoacetophenone, cyclopropanes, Lewis acids, transesterification, gallium trichloride.

1,3-Dipolar cycloaddition to unsaturated compounds is a common reaction of aliphatic diazo compounds. Alkenes normally yield 1- or 2-pyrazolines,[1] which can further be transformed into compounds of other types,[2] including biologically active ones.[3] Except for alkenes containing electron-withdrawing substituents or a strained double bond, prolonged keeping or heating is mostly required for these reactions to occur. In some cases, 1,3-dipolar cycloaddition can be promoted by a combination of heating with catalysis by pyridine[4] or molybdenum hexacarbonyl.[5] Recently,[6] we have demonstrated that the rate of cycloaddition of diazo esters to activated alkenes is increased by several orders of magnitude in the presence of some Lewis acids. Specifically, the use of $GaCl_3$ catalyzes not only 1,3-dipolar cycloaddition but also subsequent insertion of the electrophilic fragment $CHCO_2Me$ of methyl diazoacetate into the N—H bond of the resulting 2-pyrazolines.

Results and Discussion

In the present work, we studied the effects of Lewis acids on diazo ketones as well as on their reactions with activated alkenes. Under normal conditions with no Lewis acids employed, diazoacetone (**1a**) and diazoacetophenone (**1b**) slowly and regioselectively react with methyl acrylate (**2**) according to the 1,3-dipolar cycloaddition pattern. Isomerization of primary 1-pyrazolines leads to 2-pyrazolines **3a**,**b**, in which the double bond is conjugated with the keto group (Scheme 1).

Scheme 1



1a,b **3a,b** (75—83%)

R = Me (**a**), Ph (**b**)

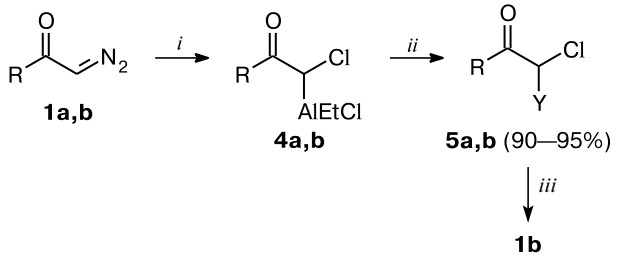
Conditions: 25 °C, 3 days.

We tried several Lewis acids ($SnCl_4$, $TiCl_4$, $BF_3 \cdot Et_2O$, $EtAlCl_2$, $In(OTf)_3$, $Sn(OTf)_2$, $Yb(OTf)_3$, and $Sc(OTf)_3$) as catalysts for this reaction. However, they all fell short of the expected effect observed earlier[6] in reactions with diazo esters. For instance, $Sc(OTf)_3$ and $Yb(OTf)_3$ increase the rate of the 1,3-dipolar cycloaddition of diazo esters to acrylates by nearly two orders of magnitude[6] but fail with substrates **1** and **2**. The aforementioned tin, titanium, aluminum, boron, and indium compounds promptly break down the starting diazo ketones **1a**,**b**, yet forming no adducts with acrylates. For instance, compounds **1a**,**b** readily react with $EtAlCl_2$ to give relatively stable organoaluminum intermediates **4a** or **4b**, which prove to be inert toward an alkene (Scheme 2). When treated with water or methanol, compounds **4** instantaneously eliminate ethane to give α-chloro ketones **5**. That is why these Lewis acids are not very convenient for use as catalysts for 1,3-dipolar cycloaddition.

* On the occasion of the 80th anniversary of the N. D. Zelinsky Institute of Organic Chemistry of the Russian Academy of Sciences.

Published in Russian in *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 2, pp. 0404—0408, February, 2014.

Scheme 2

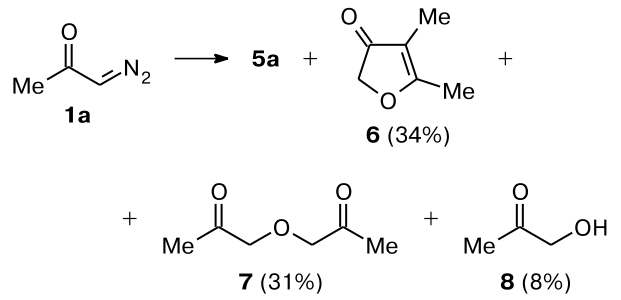


Reagents and conditions: *i.* $EtAlCl_2$, 1 min, CH_2Cl_2/hexane; *ii.* MeOY or Y_2O (Y = H, D); *iii.* $GaCl_3$ (H_2O), CH_2Cl_2, 5 min.

R = Me (**a**), Ph (**b**)

Unlike the Lewis acids discussed above, gallium trichloride behaves in a different way. In the absence of water, $GaCl_3$ slowly decomposes diazoacetone into chloroacetone **5a** and unidentified products. When treating compound **1a** with an equimolar amount of $GaCl_3$ in the system CH_2Cl_2—HCl—H_2O, we discovered an unusual transformation of diazoacetone leading to compounds **6** and **7** (Scheme 3).

Scheme 3



Reagents and conditions: $GaCl_3$ in CH_2Cl_2 and 5% HCl, 5 min.

An intermediate complex of hydroxyacetone with $GaCl_3$ (**A**), which is formed by partial hydration of compound **1a**, seems to be crucial for the formation of furan-3(2*H*)-one **6** and ether **7**. Intermediate **A** attacked by a second diazoacetone molecule on the hydroxy group is transformed into compound **7**, while an attack on the carbonyl group of **A** followed by migration of the methyl group and elimination of water gives furanone **6** (Scheme 4).

Unlike diazoacetone, diazoacetophenone **1b** does not undergo such transformations: its reaction with $GaCl_3$ in both the presence and in the absence of water promptly gives chloroacetophenone **5b** in high yield (see Scheme 2), the process being even promoted by the presence of water.

Nevertheless, gallium trichloride is the only Lewis acid that favors reactions of diazo ketones **1a**,**b** with unsaturated compounds (specifically, with methyl acrylate). As opposed to their noncatalytic transformations, $GaCl_3$-catalyzed reactions proceed quite rapidly, being completed within 15 min. Unlike diazo esters,[6] these diazo ketones mostly react by eliminating nitrogen gas. A reaction of diazoacetone with methyl acrylate in the presence of anhydrous $GaCl_3$ gives cyclopropane derivative **9a** as the only intermolecular product. This is a 3.5 : 1 mixture of *E*- and *Z*-isomers (Scheme 5). Unfortunately, much of diazoacetone under these conditions is transformed into chloroacetone **5a**. Since the presence of moisture traces appreciably increases its fraction, the yield of cyclopropane **9a** is moderate (48—54%) even when the reaction is carried out in a dry inert environment and a threefold excess of methyl acrylate is used (Table 1). The reaction products were isolated by column chromatography on silica gel and identified by ^1H and ^{13}C NMR spectroscopy. It should be noted that cyclopropanes are not formed from diazo esters in reactions catalyzed by Lewis acids: the predominant pathway leads to 2-pyrazolines with a multiple increase in the reaction rate.[6]

Scheme 4

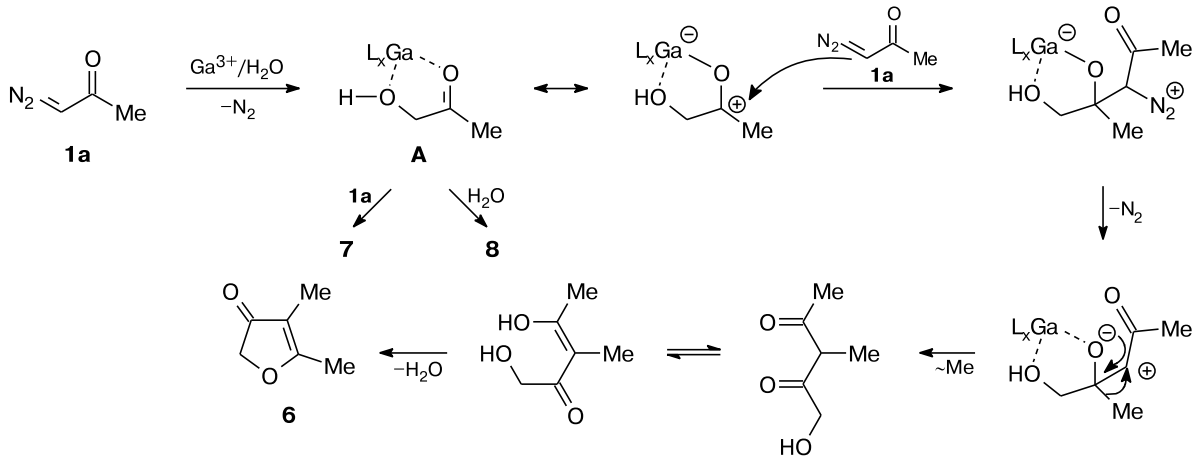
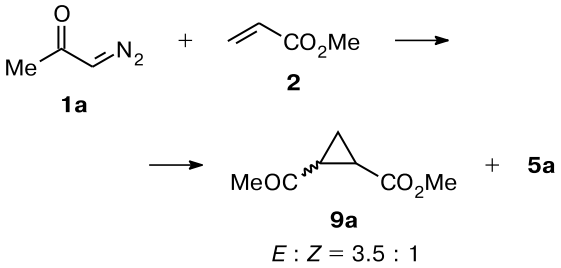


Table 1. Reaction products obtained from diazo ketones **1a**,**b** and methyl acrylate (**2**) in CH_2Cl_2 in the presence of $GaCl_3$

Diazo ketone	Molar ratio of reagents				Yield (%)			
	1	**2**	$GaCl_3$	H_2O	**9**	**10**	**11**	**12**
1a	1	3	0.2	—	48	—	—	—
1a	1	3	1	—	54	—	—	—
1b	1	3	0.2	—	36	—	5	—
1b	1	3	1	—	55	3	10	—
1b	1	3	1	2	25	—	52	<5
1b	3	1	1	2	15	—	21	46

Scheme 5



E : *Z* = 3.5 : 1

Reagents and conditions: $GaCl_3$ (H_2O), CH_2Cl_2, 20 °C, 15 min.

As with diazoacetone **1a**, a reaction of diazoacetophenone **1b** with excess methyl acrylate in the presence of anhydrous $GaCl_3$ produces chloroacetophenone and cyclopropane **9b** as a 2.6 : 1 mixture of *E*- and *Z*-isomers in 36% yield (Scheme 6, see Table 1). The use of an equimolar amount of $GaCl_3$ increases the yield of cyclopropane **9b** to 55%. In addition, small amounts of N-alkylated pyrazoline **10** and isomeric 2-benzoylcyclopropanecarboxylates **11** are detected (see Table 1). Interestingly, while a threefold excess of methyl acrylate (**2**) is employed, the reaction yields minor products **10** and **11** as a result of the addition of two diazoacetophenone molecules to methyl acrylate.

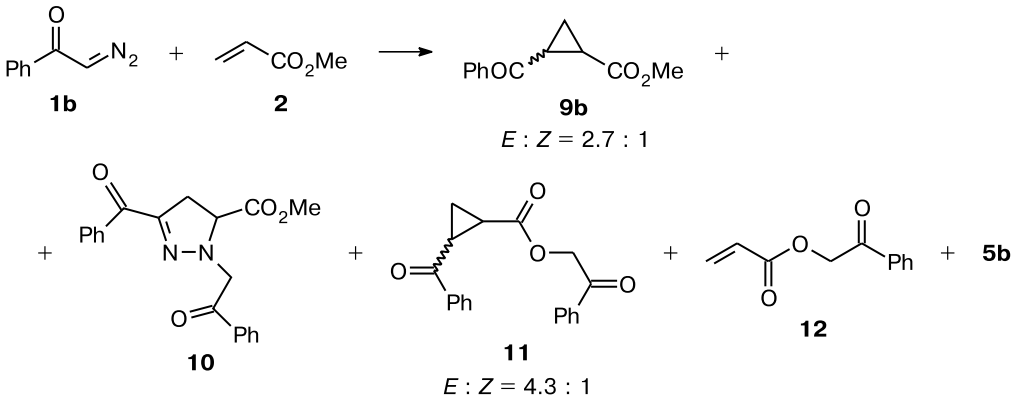
We assumed that the formation of transalkylated esters **11** could be attributed to moisture traces that persist in the reaction mixture despite great care taken to prevent this. Indeed, the use of two equivalents of water in the reaction of diazoacetophenone **1b** with compound **2** in the presence of $GaCl_3$ substantially changes the ratio of the products (see Table 1). Strange as it may seem, derivative **11** becomes a major product when an excess of methyl acrylate is used and so does compound **12** in the reaction with an excess of the diazo ketone, although the formation of product **12** results from transesterification of methyl acrylate.

Compounds **11** and **12** are both formed by transesterification of methyl carboxylates with diazoacetophenone in the presence of gallium derivatives; in the absence of water, no transesterification occurs. Such processes have not been documented hitherto. Derivative **11** is a ~4 : 1 mixture of *E*- and *Z*-isomers; *i.e.*, its formation is more selective than that of compound **9b**. Apparently, the first step involves cyclopropanation of methyl acrylate, which is followed by transesterification of intermediate **9b**. The reaction products can easily be separated by column chromatography on silica gel. It should be noted that such processes have not been observed with diazo esters.[6]

To sum up, we were the first to perform direct cyclopropanation of methyl acrylate with diazoacetone and diazoacetophenone in the presence of gallium trichloride. Previous attempts at this cyclopropanation failed because such classic catalysts as copper, palladium, and rhodium derivatives commonly used to decompose diazo compounds are inefficient or unsuitable at all for cyclopropanation of electron-deficient alkenes such as methyl acrylate.

The main role of $GaCl_3$ consists in its coordination to the ester group of methyl acrylate, producing reactive complex **13**. This complex reacts with diazo ketone **1** prior to its decomposition by the Lewis acid (Scheme 7). The first

Scheme 6



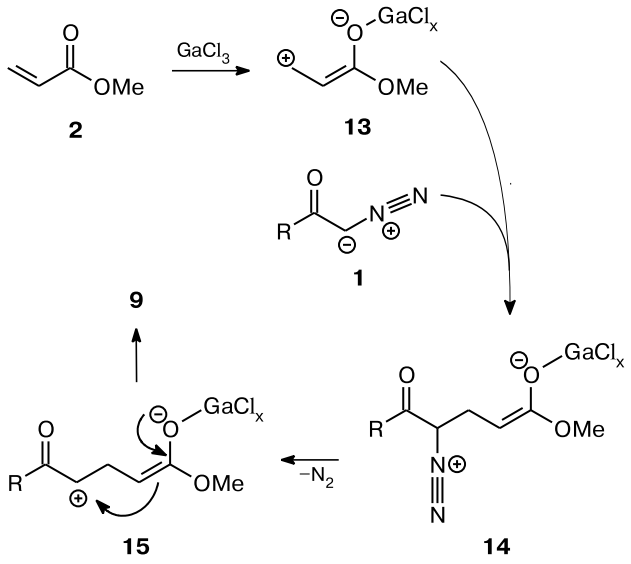
E : *Z* = 2.7 : 1

E : *Z* = 4.3 : 1

Reagents and conditions: $GaCl_3$ (H_2O); CH_2Cl_2, 20 °C, 15 min.

reaction intermediate **14** eliminates a nitrogen molecule so quickly that no cyclization into a pyrazoline ring occurs. (Apparently, similar intermediates formed from diazo esters are much more stable, and their cyclization into pyrazolines is preferred to elimination of N_2.[6]) The elimination of a nitrogen molecule from compound **14** gives intermediate **15**, which undergoes cyclization into cyclopropane **9**. Note that the formation of an unsaturated compound by possible deprotonation of intermediate **15** was not observed. In the presence of $GaCl_3$, compounds **1**, **2**, and **9**, as well as their reaction intermediates, can undergo alternative transformations (*e.g.*, transesterification and NH insertion).

Scheme 7



Experimental

^1H and ^{13}C NMR spectra were recorded on a Bruker AMX-400 spectrometer (400.1 and 100.6 MHz, respectively) in $CDCl_3$ containing 0.05% Me_4Si as an internal standard. The signals were assigned, and the ratio of isomeric reaction products was determined, using homo- and heteronuclear 1D and 2D correlation experiments (DEPT, COSY, NOESY, HSQC, and HMBC). High-resolution mass spectra (ESI-HRMS) were recorded on a micrOTOF instrument. Thin-layer chromatography was carried out on Silufol plates (Merck). For column chromatography, Merck 60 silica gel (0.040—0.063 mm) was used. Anhydrous $GaCl_3$ was purchased from Aldrich and always handled under dry argon. Reagent-grade solvents (>99.5% purity) were used without further purification. Dichloromethane was dried with granulated KOH and distilled over P_2O_5 under dry argon.

Reactions of diazo ketones 1a,b with $EtAlCl_2$. A 1 *M* solution of $EtAlCl_2$ (1.2 mL, 1.2 mmol) in hexane was added to a stirred solution of diazo ketone **1a** or **1b** (1 mmol) in CH_2Cl_2 (2.5 mL). The resulting mixture was vigorously stirred at 20 °C for 1 min. Then MeOH or CD_3OD (1 mL) was added. The reaction mixture was acidified with 10% HCl to pH 1—2, and the product was extracted with CH_2Cl_2 (3×10 mL). The combined organic extracts were dried with $MgSO_4$ and concentrated *in vacuo* to give chlorinated ketones **5a** or **5b** (or their deuterated analogs). The ^1H and ^{13}C NMR spectra of compounds **5a** or **5b** agree with the literature data.[7—9]

Reaction of diazo ketone 1a with $GaCl_3$ in the system CH_2Cl_2—HCl—H_2O. A solution of $GaCl_3$ (314 mg, 1.78 mmol) in CH_2Cl_2 (0.5 mL) was added to a stirred solution of diazoacetone **1a** (152 mg, 1.8 mmol) in CH_2Cl_2 (2.5 mL). This was immediately followed by addition of 5% HCl (3 mL). The reaction mixture was vigorously stirred at ~20 °C for 5 min until gas evolution ceased. Organic materials were extracted with CH_2Cl_2 (3×10 mL). The combined organic extracts were dried with anhydrous $MgSO_4$ and concentrated *in vacuo*. The residue was separated by column chromatography on silica gel with benzene—AcOEt as an eluent (gradient elution from 5 : 1 to 1 : 10). All products were obtained as colorless oils. They included chloroacetone (**5a**) (34 mg, 20%), 4,5-dimethylfuran-3(2*H*)-one (**6**) (35 mg, 34%), 1,1′-oxydi(propan-2-one) (**7**) (36 mg, 31%), and 1-hydroxypropan-2-one (**8**) (10 mg, 8%). The ^1H and ^{13}C NMR spectra of compounds **5a**, **7**, and **8** agree with the literature data.[7,8,10,11]

4,5-Dimethylfuran-3(2*H*)-one (6). ^1H NMR, δ: 1.68 (s, 3 H, MeC(4)); 2.20 (s, 3 H, MeC(5)); 4.45 (s, 2 H, CH_2). ^{13}C NMR, δ: 5.4 (MeC(4)); 15.0 (MeC(5)); 74.0 (CH_2), 111.7 (C(4)); 186.6 (C(5)); 203.3 (C(3)). Found (%): C, 64.08; H, 7.12. $C_6H_8O_2$. Calculated (%): C, 64.27; H, 7.19.

α-Chloroacetophenone (5b). Anhydrous $GaCl_3$ (290 mg, 1.64 mmol) was added to a stirred solution of diazoacetophenone **1b** (200 mg, 1.37 mmol) in CH_2Cl_2 (3 mL). The reaction mixture was vigorously stirred at 20 °C for 5 min and acidified with 10% HCl to pH 1—2. The product was extracted with CH_2Cl_2 (3×10 mL). The combined organic extracts were dried with anhydrous $MgSO_4$ and concentrated *in vacuo*. The yield of α-chloroacetophenone was 192 mg (91%), colorless crystals, m.p. 55—57 °C. The ^1H and ^{13}C NMR spectra of compound **5b** agree with the literature data.[9]

Reactions of diazo ketones 1a and 1b with methyl acrylate in the presence of $GaCl_3$ (general procedure). Anhydrous $GaCl_3$ (0.2 or 1 mmol, see Table 1) was added in one portion under argon to a stirred solution of diazo ketone **1a** or **1b** (1 mmol) and methyl acrylate (3 mmol) in dry CH_2Cl_2 (3 mL). The mixture was stirred at 20 °C for 15 min and acidified with 10% HCl to pH 1—2. Organic materials were extracted with CH_2Cl_2 (3×10 mL). The combined organic extracts were dried with anhydrous $MgSO_4$ and concentrated *in vacuo*. The residue was separated by column chromatography on SiO_2 with benzene—AcOEt (10 : 1) as an eluent. For the yields of the compounds obtained, see Table 1.

Methyl 2-acetylcyclopropanecarboxylate (9a) was obtained from diazoacetone **1a** (85 mg, 1 mmol) and methyl acrylate (255 mg, 3 mmol) in the presence of $GaCl_3$ (34 mg, 0.2 mmol). Yield 68 mg (48%), a ~3.5 : 1 mixture of *E*- and *Z*-isomers (isolated by column chromatography). With an increased amount of $GaCl_3$ (175 mg, 1 mmol), the yield of compound **9a** was 77 mg (54%). The ^1H and ^{13}C NMR spectra of this product agree with the literature data.[12,13]

Methyl 2-benzoylcyclopropanecarboxylate (9b) was obtained from diazoacetophenone **1b** (145 mg, 1 mmol) and methyl acrylate (255 mg, 3 mmol) in the presence of $GaCl_3$ (34 mg, 0.2 mmol). Separation by column chromatography gave isomers *E*-**9b** (53 mg, 26%) and *Z*-**9b** (21 mg, 10%) and small fractions con-

taining compound **10** (~3%) and a ~4 : 1 mixture of minor cyclopropanes *E*- and *Z*-**11** (~5 or 10%; ^{1}H NMR data) (see Table 1). With an increased amount of $GaCl_3$ (175 mg, 1 mmol), the yields of *E*-**9b** and *Z*-**9b** were 82 (40%) and 31 mg (15%), respectively. The ^{1}H and ^{13}C NMR spectra of cyclopropanes *E*-**9b** and *Z*-**9b** agree with the literature data.[14] The procedure for isolation of cyclopropanes *E*- and *Z*-**11** is described below, followed by their characteristics.

Methyl 3-benzoyl-1-(2-oxo-2-phenylethyl)-4,5-dihydro-1*H*-pyrazole-5-carboxylate (10). Colorless oil, ~90% purity. ^{1}H NMR, δ: 3.47 (dd, 1 H, H_a(4), ^2J = 17.5 Hz, ^3J = 10.6 Hz); 3.66 (dd, 1 H, H_b(4), ^2J = 17.5 Hz, ^3J = 13.4 Hz); 3.78 (s, 3 H, OMe); 4.75 (dd, 1 H, H(5), ^3J = 13.4 Hz, ^3J = 10.6 Hz); 5.01 and 5.22 (both d, 1 H each, CH_2, ^2J = 18.1 Hz); 7.35—7.65 (m, 6 H, *m*-H_{Ph} and *p*-H_{Ph}); 7.96 and 8.07 (both m, 4 H, *o*-H_{Ph}).

Reaction of diazoacetophenone with methyl acrylate in the presence of $GaCl_3$ and water. ***A.*** Anhydrous $GaCl_3$ (125 mg, 0.7 mmol) was added in one portion to a solution of diazoacetophenone (103 mg, 0.7 mmol), methyl acrylate (180 mg, 2.1 mmol), and water (26 mg, 1.4 mmol) in CH_2Cl_2 (3 mL). The reaction mixture was stirred at ~20 °C for 15 min and worked up according to the general procedure. Separation by column chromatography on SiO_2 with benzene—AcOEt (10 : 1) as an eluent afforded compounds *E*-**9b** (26 mg, 18%), *E*-**11** (45 mg, 42%), *Z*-**9b** (10 mg, 7%), and *Z*-**11** (11 mg, 10%) as colorless oils and a small fraction containing compound **12** (<5% yield).

B. A similar reaction of compound **1b** (208 mg, 1.4 mmol) with methyl acrylate (40 mg, 0.48 mmol) in the presence of water (18 mg, 1 mmol) and $GaCl_3$ (86 mg, 0.48 mmol) gave 2-oxo-2-phenylethyl acrylate (**12**) (42 mg, 46%) as a colorless oil and cyclopropanes *E*- and *Z*-**9b** and *E*- and *Z*-**11** in a total yield of 43 mg (see Table 1). The products were separated by column chromatography on SiO_2 with benzene—AcOEt (10 : 1) as an eluent. The ^{1}H and ^{13}C NMR spectra of compounds **9b** and **12** agree with the literature data.[14,15]

2-Oxo-2-phenylethyl *E*-2-benzoylcyclopropanecarboxylate (*E*-11). ^{1}H NMR, δ: 1.70 (ddd, 1 H, H_a(3), ^2J = 3.7 Hz, ^3J = 8.5 Hz, ^3J = 5.7 Hz); 1.74 (ddd, 1 H, H_b(3), ^2J = 3.7 Hz, ^3J = 8.5 Hz, ^3J = 6.0 Hz); 2.55 (ddd, 1 H, H(1), ^3J = 8.5 Hz, ^3J = 5.7 Hz, ^3J = 3.7 Hz); 3.31 (ddd, 1 H, H(2), ^3J = 8.5 Hz, ^3J = 6.0 Hz, ^3J = 3.7 Hz); 5.36 and 5.41 (both d, 1 H each, OCH_2, ^2J = 16.3 Hz); 7.44—7.65 (m, 6 H, *m*-H_{Ph} and *p*-H_{Ph}); 7.92 and 8.07 (both m, 4 H, *o*-H_{Ph}). ^{13}C NMR, δ: 17.9 (C(3)); 24.5 (C(1)); 26.6 (C(2)); 66.5 (OCH_2); 127.9, 128.6, 128.8, and 129.1 (*o*-CH_{Ph} and *m*-CH_{Ph}); 133.5 and 134.1 (2 *p*-CH_{Ph}); 134.4 and 137.2 (2 *ipso*-C_{Ph}); 171.9 (COO); 192.0 and 197.0 (2 CO). $C_{19}H_{16}O_4$. Calculated: [M + Na], 331.0941. Found: *m/z* 331.0939.

2-Oxo-2-phenylethyl *Z*-2-benzoylcyclopropanecarboxylate (*Z*-11). ^{1}H NMR, δ: 1.48 (ddd, 1 H, H_a(3), ^2J = 4.8 Hz, ^3J = 8.6 Hz, ^3J = 8.5 Hz); 2.01 (ddd, 1 H, H_b(3), ^2J = 4.8 Hz, ^3J = 7.1 Hz, ^3J = 6.7 Hz); 2.51 (ddd, 1 H, H(1), ^3J = 8.7 Hz, ^3J = 8.5 Hz, ^3J = 6.7 Hz); 2.89 (ddd, 1 H, H(2), ^3J = 8.7 Hz, ^3J = 8.6 Hz, ^3J = 7.1 Hz); 5.18 and 5.28 (both d, 1 H each, OCH_2, ^2J = 16.4 Hz); 7.36—7.60 (m, 6 H, *m*-H_{Ph} and *p*-H_{Ph}); 7.83 and 8.04 (both m, 4 H, *o*-H_{Ph}). ^{13}C NMR, δ: 12.6 (C(3)); 22.8 (C(1)); 26.5 (C(2)); 66.4 (OCH_2); 127.9, 128.5, 128.7, and 129.0 (*o*-CH_{Ph} and *m*-CH_{Ph}); 133.3 and 133.9 (2 *p*-CH_{Ph}); 134.2 and 136.7 (2 *ipso*-C_{Ph}); 169.7 (COO); 192.1 and 194.8 (2 CO). $C_{19}H_{16}O_4$. Calculated: [M + Na], 331.0941. Found: *m/z* 331.0937.

This work was financially supported by the Division of Chemistry and Materials Sciences of the Russian Academy of Sciences (Basic Research Program "Theoretical and Experimental Study of the Nature of Chemical Bonding and the Mechanisms of Essential Chemical Reactions and Processes) and the Council on Grants at the President of the Russian Federation (State Support Program for Leading Scientific Schools of the Russian Federation, Grant NSh-604.2012.3).

References

1. M. Regitz, H. Heydt, *1,3-Dipolar Cycloaddition Chemistry*, Ed. A. Padwa, Wiley Interscience, New York, 1984, Vol. **1**, p. 393.
2. G. Mass, in *Synthetic Applications of 1,3-Dipolar Cycloaddition Chemistry Toward Heterocycles and Natural Products*, Eds A. Padwa, W. H. Pearson, Wiley and Sons, Hoboken (NJ), 2003, p. 539.
3. T. Kano, T. Hashimoto, K. Maruoka, *J. Am. Chem. Soc.*, 2006, **128**, 2174.
4. M. P. Doyle, M. R. Colsman, R. L. Dorow, *J. Heterocycl. Chem.*, 1983, **20**, 943.
5. M. P. Doyle, R. L. Dorow, W. H. Tamblyn, *J. Org. Chem.*, 1982, **47**, 4059.
6. R. A. Novikov, D. N. Platonov, V. A. Dokichev, Yu. V. Tomilov, O. M. Nefedov, *Russ. Chem. Bull.* (*Int. Ed.*), 2010, **59**, 984 [*Izv. Akad. Nauk, Ser. Khim.*, 2010, 963].
7. T. R. Doi, R. Rittner, F. Yoshinaga, C. F. Tormena, R. J. Abraham, *Spectrochim. Acta, Part A*, 2005, **61**, 2221.
8. K. Griesbaum, R.-O. Quinkert, K. J. McCullough, *Eur. J. Org. Chem.*, 2004, 3657.
9. L. Gu, T. Lu, L. Tou, M. Zhang, Y. Zhang, *Adv. Synth. Catal.*, 2013, **355**, 1077.
10. J. Zhou, B. List, *J. Am. Chem. Soc.*, 2007, **129**, 7498.
11. P. Gogoi, G. K. Sarmah, D. Konwar, *J. Org. Chem.*, 2004, **69**, 5153.
12. T. Saegusa, K. Yonezawa, I. Murase, T. Konoike, S. Tomita, Y. Ito, *J. Org. Chem.*, 1973, **38**, 2319.
13. D. Romo, J. L. Romine, W. Midura, A. I. Meyers, *Tetrahedron*, 1990, **46**, 4951.
14. F. Hammerschmidt, E. Zbiral, *Justus Liebigs Ann. Chem.*, 1977, 1026.
15. P. M. Joensuu, H. W. Lam, *Org. Lett.*, 2005, **7**, 4225.

Received December 4, 2013