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Metal-free intramolecular cyclopropanation of alkenes through iodonium ylide methodology

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ABSTRACT

Intramolecular cyclopropanation of alkenes occurs thermally with iodonium ylides in the absence of conventional metal catalysts such as Rh(II) and Cu(II). In rigid molecular systems conversions are near quantitative. A mechanism is proposed involving formal 2+2 cycloaddition followed by reductive elimination of PhI to yield the cyclopropane.

1. Introduction

The cyclopropane ring can be regarded as a unique functional group that can undergo transformations that are more difficult or impossible with many of the conventional carbon-based functional groups. Due to inherent ring strain, i.e., 27.5 kcal/mol, cyclopropane is unparalleled among carbocycles in both its properties and reactivity.[1] Thus, cyclopropane derivatives provide building blocks of considerable synthetic potential.[2] Many synthetic and metabolite cyclopropane ring containing natural products such as curacin A,[3,4] cilastatin,[5] ambruticin,[6,7] and solandelactone A[8] possess biological properties ranging from enzyme inhibition to antibiotic, antiviral, antitumor, and neurochemical properties (Fig. 1).[9]

Staudinger et al. isolated and characterized the cyclopropane-containing natural insecticide, (+)-*trans*-chrysanthemic acid **1** (Fig. 2), from the pyrethrum flowers (*Chrysanthemum cinerariaefolium* and *Chrysanthemum coccineum*).[10] The active insecticidal compounds are the esters of **1**, which have been commercially marketed to produce one of the most successful classes of biomimetic insecticides, the pyrethroids. It could be argued that the highly strained three-membered carbocycle is ubiquitous. It occurs, for example, in every green plant in the form of 1-aminocyclopropanecarboxylic acid (ACC) **2** (Fig. 2), a direct precursor to the plant hormone ethylene.[11]

In terms of chemical reactivity, cyclopropanes substituted with donor and acceptor groups (Fig. 3) dramatically activate the cyclopropane ring toward substitution and hence, a high versatility of products may be formed after ring cleavage.[12,13] Since the two charges of synthon **6** are carbon atoms in a 1,3-relationship, reactions employing **3** may be regarded as processes, which provide products not easily available by alternative methods.[14]

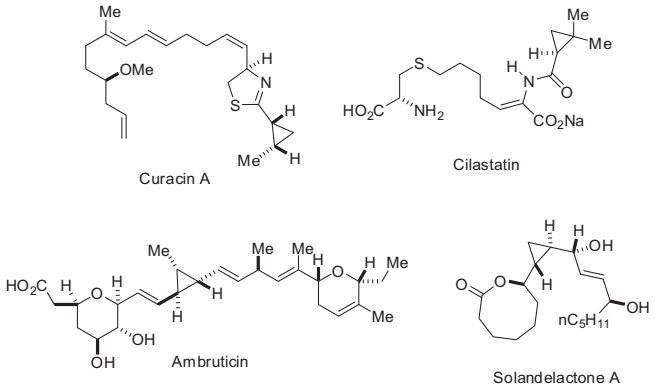

Figure 1. Cyclopropane ring containing natural products and drugs.

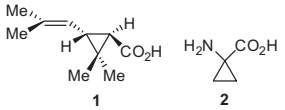

Figure 2.

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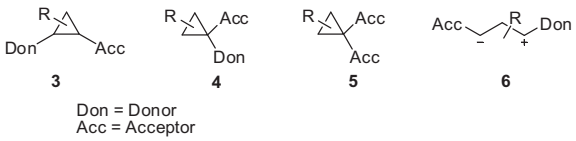


Figure 3.

1.1. Preparation of cyclopropane rings from diazo compounds

Since their discovery, carbene transfer to alkenes has been a method of choice for the preparation of cylopropane rings. The formal addition of a carbene group from a diazo compound to an unsaturated double bond has been extensively developed in the last decades.[15–17] Although such a process was initially induced either thermally or photochemically, further use of transition-metal catalysts (metal carbenoids or metallo-carbenes) allowed exerting a certain control in the selectivity of this reaction. Figure 4 shows the catalytic cycle of a typical olefin cyclopropanation reaction, in which an olefin reacts with a diazo compound in the presence of a metal catalyst.

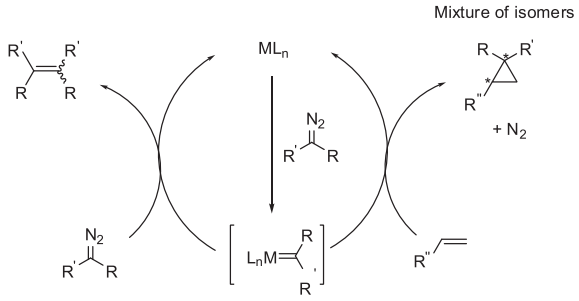


Figure 4.

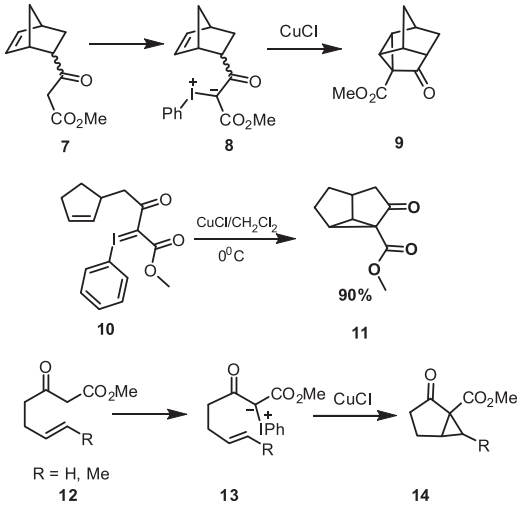
Substituted olefins lead to the formation of two diastereoisomers, cis and trans (assuming that the substituents of the diazo compound are different), each of them corresponding to a mixture of two enantiomers. The transition metal-catalyzed decomposition of diazo compounds leads to metallo-carbenes, which are not isolable, but transfer the carbene moiety to a suitable acceptor molecule or to an appropriate acceptor site within the metallo-carbene.[18] Also, the metal catalysts based on copper(I), copper(II), and rhodium(II) can induce the catalytic coupling of the diazo compound, an undesired reaction that diminishes the yields of cyclopropanes. Thus, the use of diazo compounds might be avoided if it were possible to generate the metallo-carbenes from other sources, i.e., iodonium ylides. Sometimes diazo compounds fail to afford desired products even in presence of metal catalysts as in the case of the diazo analogue of Meldrum's acid ylide **25** (Scheme 4), which failed to undergo diazo decomposition when exposed to Rh(II) carboxylate catalysts even at elevated temperatures. However, iodonium ylide **25**, as discussed below, afforded the cyclopropane at relatively low temperatures.[19]

1.2. From iodonium ylides

Iodonium ylides provide a safer alternative to the highly hazardous (explosive carcinogens) diazo compounds. The photochemical,[20] thermal[21–23] or transition metal-catalyzed[20,24–26] decomposition of phenyliodonium ylides affords products typical for carbene or metal carbenoid intermediates. A large number of efficient and selective catalysts, mostly based on Cu(I) or Rh(II), are now available for carbenoid reactions, such as cyclopropanation of olefins. The reaction mechanism involves interaction of the catalyst with the phenyliodonium ylide or corresponding diazo compound, to afford a metallo-carbene intermediate with concomitant release of iodobenzene or nitrogen and subsequent transfer of the carbene to an appropriate substrate. The mechanism of these reactions is, however, controversial. Carbene or carbenoid pathways have often been proposed or assumed, but experimental support of these hypotheses is scarce. Enantiocontrol in the carbene transfer step may be achieved by chiral ligands surrounding the metal center of the catalyst. Iodonium ylides are readily accessible by reaction of C–H acidic compounds with iodobenzene diacetate, PhI(OAc)$_2$.[27] They occur as amorphous solids or oils. Often, their decomposition occurs at temperatures well below than those required for diazo decomposition.

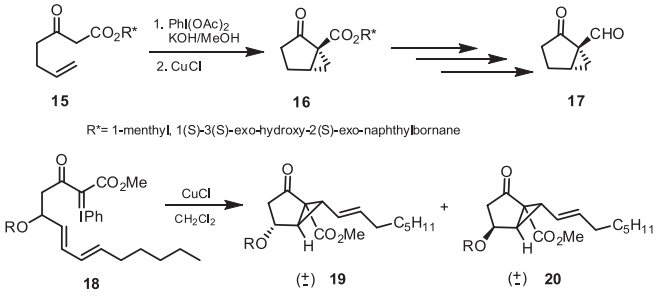
1.3. Copper-catalyzed cyclopropanation

The majority of the synthetically useful transformations with phenyliodonium ylides have been carried out under Cu-catalysis, and for Cu-catalysts the mechanism is not established. Moriarty et al. investigated the intramolecular cyclopropanation of ylide **10** (Scheme 1) to the tricyclic ketone **11** in the presence of copper(I) chloride.[28–31]



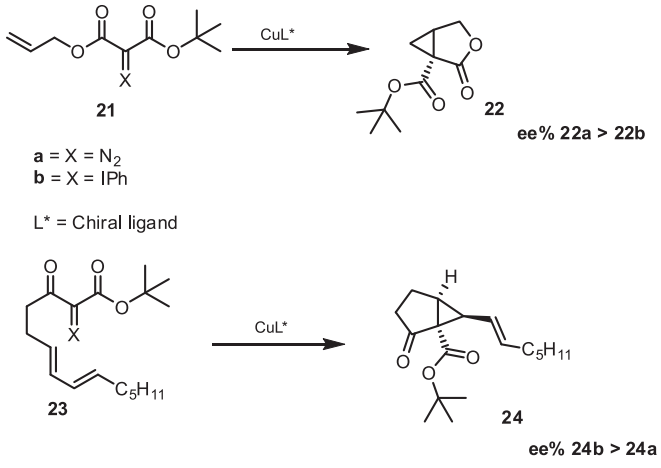
Scheme 1.

The authors demonstrated the application of intramolecular copper(I) catalyzed cyclopropanation of iodonium ylides by initially synthesizing **9**. They used it for the preparation of compound **14**, which was the precursor for **17**. Using this methodology **18** was converted as mixture of diastereomers **19** and **20** of natural products such as prostaglandins and vitamin D, respectively (Scheme 2).



Scheme 2.

However, a controversy ensued over the reaction mechanism. Moriarty et al. found that the reaction worked in absence of any metal catalysts; the authors suggested that the reaction may not be occurring via a copper–carbenoid intermediate; but rather copper plays a role in electron transfer. Mueller et al. did a comparative study with diazomalonates and diazoacetoacetates and corresponding iodonium ylides in the presence of chiral copper catalysts (Scheme 3).[32]



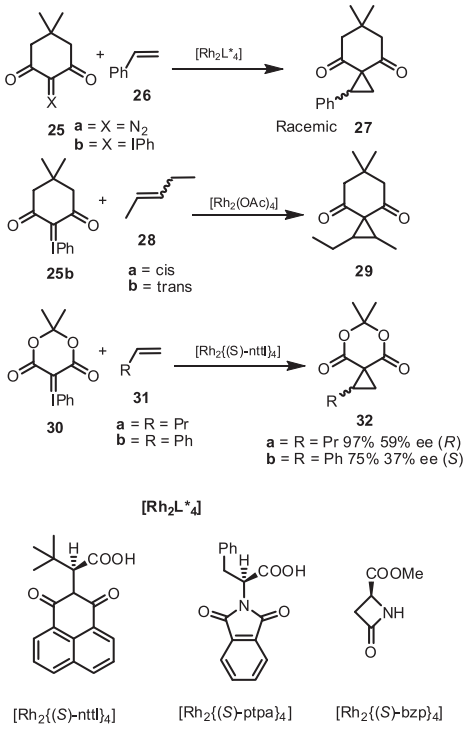
Scheme 3.

These authors reported the observation of asymmetric induction in the Cu-catalyzed reactions of the ylides **21** and **23**, which is consistent with a carbenoid mechanism; however, the discrepancy of the enantioselectivities observed between diazo compounds **21a** and **23a** and corresponding ylides **21b** and **23b** (Scheme 3) suggests a competing nonselective pathway for cyclopropanation outside of the coordination sphere of copper. The authors claimed, "However, irrespective of the reaction mechanism, the observation of significant levels of enantioselectivity implies that the reaction must take place within the coordination sphere of the metal and the ionic mechanism proposed by Moriarty can not apply."[33] These observations imply that the copper-catalyzed mechanism may involve intermediacy of a copper-carbenoid, but the same argument cannot be applied to the metal-free route.

1.4. Rhodium-catalyzed cyclopropanation

Phenyliodonium ylides are also known to undergo diverse reactions in the presence of various Rh(II) catalysts. The stereoselectivity in rhodium-catalyzed intermolecular cyclopropanation is dependent on both the alkenes and ylides used. For example, the reaction of 2-diazodimedone **25a** and the ylide **25b** exhibit very poor enantioselectivity in cyclopropanations of terminal olefins (Scheme 4). The $Rh_2(OAc)_4$-catalyzed cyclopropanation of *cis*- and *trans*-pent-2-ene (**28a** and **28b**) with phenyliodnium ylide of Meldrum's acid **25b** was stereospecific and yielded the cyclopropanes **29a** and **29b**, respectively.[34] In the presence of $[Rh_2\{(S)\text{-nttl}\}_4]$, pentene **31a** and styrene **31b** reacted with **30** to afford the cyclopropanes **32a** and **32b** with 59% and 37% ee, respectively (Scheme 4).[34]

These ee's are very similar (50%) to those obtained with corresponding diazo compounds[35] and are indicative of the similar reaction mechanism, i.e., formation of a rhodium-carbenoid intermediate in both diazo compounds and corresponding iodonium ylides. A tentative explanation for the low enantioselectivity of the diazodimedone **25a**, and the corresponding phenyliodonium ylide **25b** may be explained on the grounds of the investigations of Davies and Panaro[36] It was found that diazo esters, that are known to involve carbenoid intermediates, carrying stabilizing substituents such as phenyl or vinyl groups, exhibit significantly higher ρ-values in the cyclopropanation of substituted styrenes than the unsubstituted diazoacetate esters. A higher ρ-value implies higher selectivity, owing to a transition state occurring later on the reaction coordinate. Interestingly, the more stabilized carbenoids also exhibit higher enantioselectivities. Applying the same argument to carbenoids derived from **25a**,**b**, the absence of selectivity may be attributed to their higher reactivity in comparison, for example, to the carbenoids derived from **30**, where the oxygen atoms provide

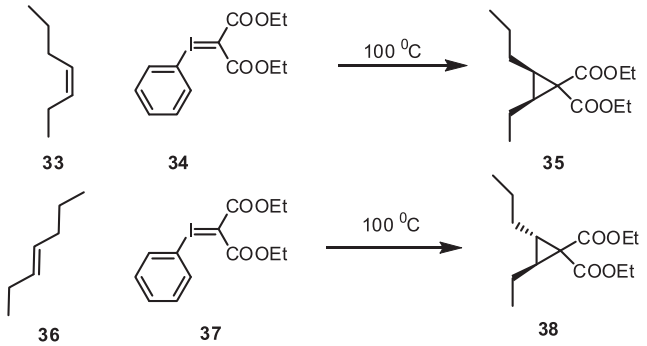


Scheme 4.

some stabilization. This is consistent with the observation of lower enantioselectivity for reactions involving diazo ketones[37] in comparison with diazo esters or diazo amides, although a few enantioselective catalysts for diazo ketones have been reported.[38–40]

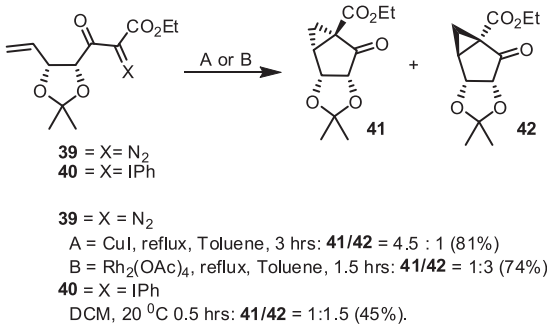
1.5. Metal-free cyclopropanation

Although transition metal-catalyzed organic transformations are highly stereoselective and efficient processes, however, due to environmental and health concerns contemporary organic chemistry strives to be metal-free. An example of metal-free cyclopropanation using phenyliodonium ylides was reported by Camacho et al.[41] Heating phenyliodonium bis(ethoxycarbonyl) methanide **34** (Scheme 5) in *cis*-heptene **33** at 100 °C afforded the *cis*-cyclopropane **35**, iodobenzene, and several minor products, while in the presence of *trans*-hept-2-ene **36**, the *trans*-cyclopropane **38** was formed.[41] According to the authors, the high stereospecificity of the reaction suggests cyclopropanation of the double bond by a singlet carbene, cyclopropanation being faster than intersystem crossing.



Scheme 5.

Contrary to the Camacho's assertions, Gallos et al. claimed that the metal-free cyclopropanation does not involve a carbene intermediate.[42] They found that refluxing ethyl 2-diazo-4,5-isopropylidene-dioxy-3-oxo-6-heptenoate **39** in toluene with a 5% molar ratio of CuI for 3 h (Scheme 6) gave a mixture of the cyclopropanation products **41** and **42** (81%, **41**/**42**=4.5:1 diastereoisomeric ratio). However, when $Rh_2(OAc)_4$ was employed as a catalyst, diazo compound **39** decomposed in 1.5 h to the same cyclopropanation products, but with opposite diastereoselectivity (74%, **41**/**42**=1:3 diastereoisomeric ratio). The phenyliodonium ylide **40**, without a metal catalyst, decomposed within 30 min in DCM solution at 20 °C, under an argon atmosphere, to again give **41** and **42**, in moderate yield and a slight preference of **42** (45%, **41**/**42**=1:1.5 diastereoisomeric ratio). Surprisingly, the same results were found with either CuI and $Rh_2(OAc)_4$.



Scheme 6.

The Gallos results suggest that the reactions may not be proceeding through a carbene intermediate. The variation of diastereoselectivities observed should originate from the different reaction mechanisms followed by the diazo compounds and iodonium ylides, under the applied conditions. The metal-catalyzed decomposition of diazo compounds proceeds most probably via a metallo-carbenoid intermediate, whereas the iodonium ylide decomposition is, in this particular case, a stepwise process with possible formation of intermediates 1 or 2 (Fig. 5). Further reductive elimination of iodobenzene affords the cyclopropane ring. Since the decomposition reaction of iodonium ylide is independent of the catalyst used (or absence of catalyst), being completed at the same time (within 30 min) and giving the same yields and diastereoselectivity, it is apparent that the metal is not coordinated with these intermediates. Furthermore, intermediate 1 leading to the formation of **42** looks less favored compared to intermediate 2, because of the stronger interactions of the bulkier iodophenyl group with one methyl of the acetonide group in intermediate 1 than the respective ones of the ethoxycarbonyl group in intermediate 2.

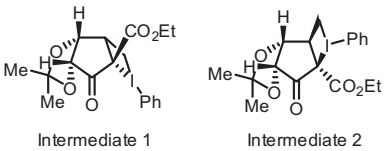
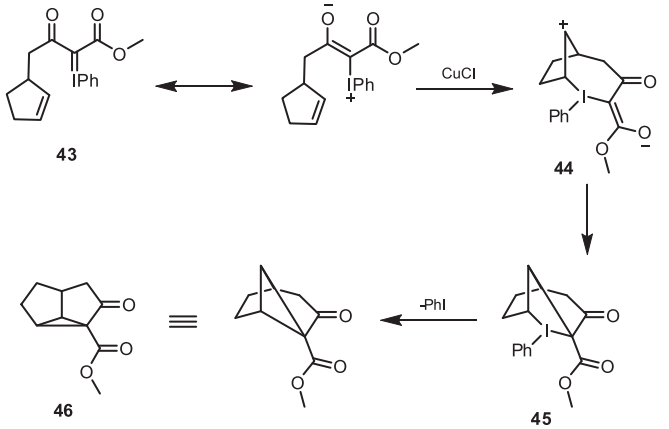


Figure 5.

2. Results and discussion

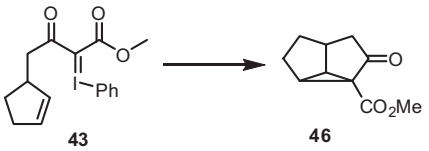
Earlier, we and others found that in the case of certain intramolecular cyclopropanation processes, conventionally effected using copper or rhodium catalysis, the reaction occurred efficiently in the absence of these metals.[19,28,42–44] Treatment of phenyliodonium ylide **43** with 10 mol % of CuCl catalyst resulted in a 90% yield of tricyclic ketone **46** (Scheme 7). The possibility of involvement of carbenoid intermediate was ruled out on the basis of the fact that no Wolff-type rearrangement products were obtained in these reactions, although corresponding α-ketocarbene derived from α-diazoketones has been shown to follow this pathway.[20,45] Also, since the reaction proceeds in the absence of the catalyst, the catalytic effect of Cu(I), in turn, was ascribed to electron transfer.



Scheme 7.

A stepwise mechanism was proposed, in which the electrophilic iodonium center of **43** attacks the C=C bond to afford a carbenium ion **44**, which, subsequently, undergoes transannular alkylation to yield **46**. In order to understand the reaction mechanism various intramolecular cyclopropanation reactions were explored. The following table shows previous attempts in our lab for intramolecular cyclopropanation of phenyliodonium ylide **43** under various catalytic, thermal and photochemical conditions (Table 1).[44]

Table 1
Intramolecular cyclopropanation of phenyliodonium ylides[a]

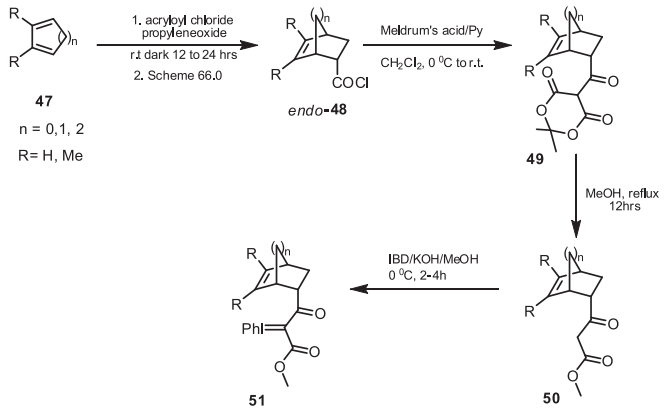


Entry	Metal catalyst	Conditions	Yield %
1	CuCl	DCM, Ar, 0 °C to rt, 2 h	95%
2	$CuCl_2$	DCM, Ar, 0 °C to rt, 2 h	58–65%
3	$Cu(acac)_2$	DCM, Ar, 0 °C to rt, 2 h	58–60%
4	$Rh_2(OAc)_4$	DCM, Ar, 0 °;C to rt, 2 h	~20%,[b] complex mix
5	$Rh_2(OAc)_4$	DCM, Ar, −40 °C to rt, 2 h	~50%,[b] complex mix
6	Thermal	DCM, reflux, 2 h	~10–12%
7	Thermal	DCM, reflux, 12 h	75%
8	Sunlamp	hv, $CDCl_3$, Ar, 3 h (heat)	65%
9	UV reactor	hv, $CDCl_3$, Ar, 3 h (cooled)	58–60%
10	$Pd(OAc)_2$	DCM, Ar, 0 °C to rt, 2 h	Complex rxn mix[b]
11	$ZnBr_2$	DCM, Ar, 0 °C to rt, 2 h	60–65%
12	$Zn(OTf)_2$	DCM, Ar, 0 °C to rt, 2 h	16–20%[a]
13	$AlCl_3$	DCM, Ar, 0 °C to rt, 2 h	15–20%[a]

[a] These catalysts do have an effect on decomposition of the ylide, but the cyclopropanated product is not the major product.
[b] The reaction mixture formed was too complicated to resolve by either HPLC or standard flash column chromatography.

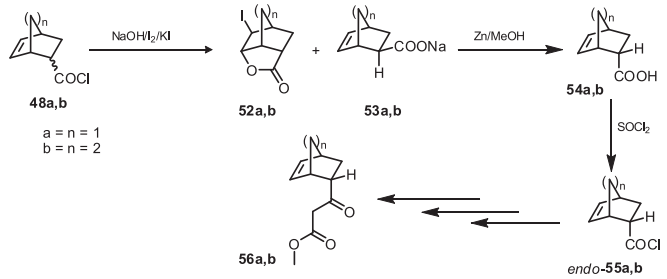
Entry 7 in above table shows the intramolecular cyclopropanation in good yields, i.e., 75% (second best to CuCl catalyzed

process) under thermal conditions. In this study only one substrate was studied in detail. Given the synthetic and biological importance of cyclopropane rings and the need for a greener route for their synthesis, we decided to study the metal-free route and extend the scope of the metal-free cyclopropanation of phenyliodonium ylides. In order to check the generality of process, various phenyliodonium ylides were prepared using methodology described in Scheme 8.



Scheme 8.

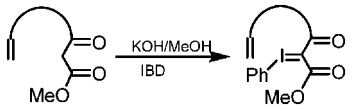
A Diels–Alder reaction between acryloyl chloride and different 1,3-dienes in presence of small amount of propylene oxide, afforded mono and bicyclic acid chlorides in almost quantitative yields. In the case of bicyclic acid chlorides mixture **48a** and **48b** isomers were obtained, which were separated by converting them to the corresponding acids (Scheme 9), followed by iodolactonization to yield **52** and **53**. Separation of the sodium salt of the *exo*-acid followed by dehalogenation using Zn gave pure *endo* isomers **54a**,**b**. These acids were then converted to the corresponding acid chlorides *endo*-**55a**,**b**, and were further used for the next step, i.e., condensation with Meldrum's acid in presence of base, without purification. For example, the resulting Meldrum's acid adduct **49** was refluxed in methanol for 4–5 h to yield substituted β-ketoesters **56a**,**b** (Scheme 9).

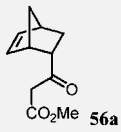
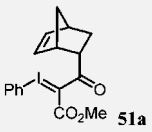
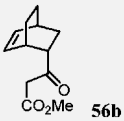
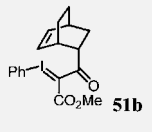
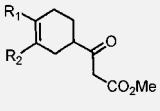
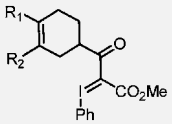
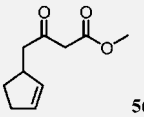
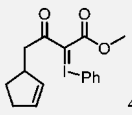


Scheme 9.

The resulting β-ketoesters **56** were treated with 10% methanolic solution of KOH, at below 0 °C for half an hour followed by addition of IBD at the same temperature to afford substituted phenyliodonium ylides (Scheme 8). Most phenyliodonium ylides were prepared at −10 °C to 0 °C and are solid at room temperature. Ylides **51** (Table 2) were very unstable at room temperature and were prepared at −78 °C and −40 °C, respectively. The crude ^{1}H NMR showed all peaks corresponding to a phenyliodonium ylide, but after keeping the samples for as little as 15 min at room temperature, decomposition of these ylides to form cyclopropanes as well as dimerization products were seen.

Table 2
Preparation of phenyliodonium ylides

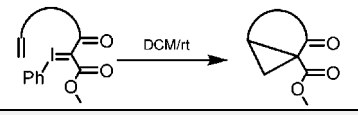


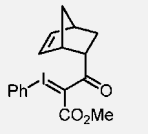
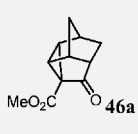
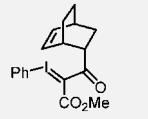
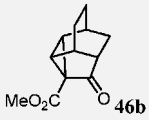
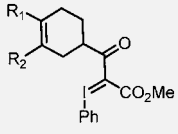
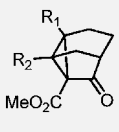
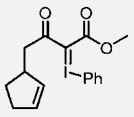
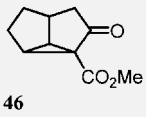
Entry	Ketoester	Ylide	Temp (°C)	Yield %
1	 **56a**	 **51a**	0	80
2	 **56b**	 **51b**	−78	69 (unstable)
				
3	R_1=H, R_2=H **56c**	**51c**	0	83
4	R_1=CH_3, R_2=H **56d**	**51d**	0	75
5	R_1=CH_3, R_2=CH_3 **56e**	**51e**	−30	60 (unstable)
6	 **56f**	 **43**	−10	93

2.1. Metal-free intramolecular cyclopropanation

Metal-free cyclopropanation was achieved by stirring above phenyliodonium ylides in dry dichloromethane for the stipulated time (Table 3). Reaction of ylide **51a** was monitored by

Table 3
Metal-free intramolecular cyclopropanation unsaturated phenylidonium ylides of β-dicarbonyl compounds



Entry	Ylide	Cyclopropane	Time	Yield %
1		 **46a**	4 h	95
2		 **46b**	15 min	55
				
3	R_1=H, R_2=H	**46c**	8 min	80
4	R_1=CH_3, R_2=H	**46d**	6 min	68
5	R_1=CH_3, R_2=CH_3	**46e**	30 min	54
6		 **46**	8 h	95

using ^{1}H NMR: a 10 mg sample was placed in an NMR tube and 0.8 mL of dry $CDCl_3$ was added. The ^{1}H NMR spectra were recorded at room temperature at 1-h intervals for 3 h. Figure 6 shows a complete conversion of starting material to cyclopropane product with a negligible amount of side products.

a carbene transition state **58**, which could be generated by thermal cleavage of C–I bond of between ylidic carbon and iodobenzene.

2.2.1. Carbene pathway. It is well documented that the copper-catalyzed, inter as well intramolecular cyclopropanation of phenyl-

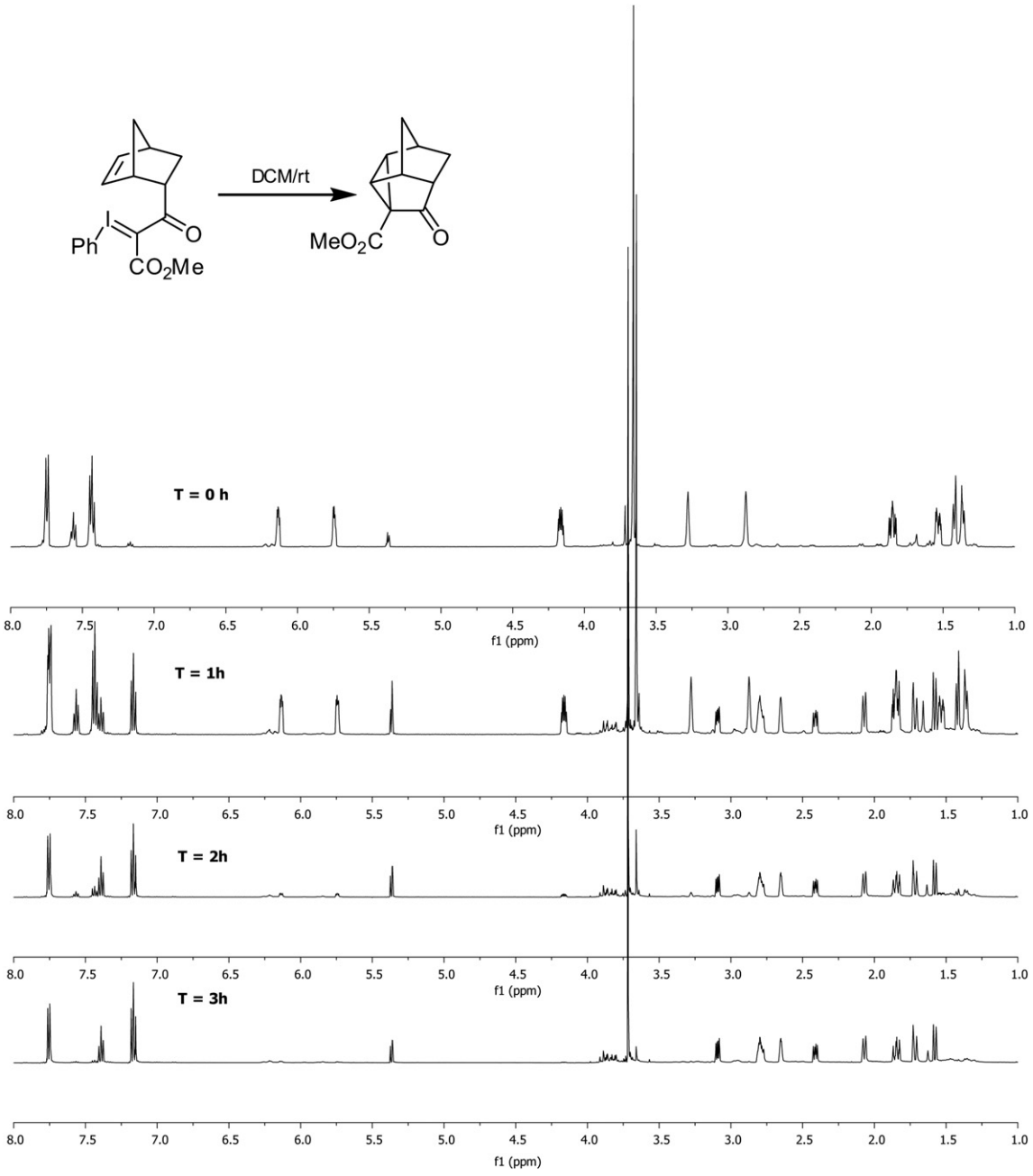
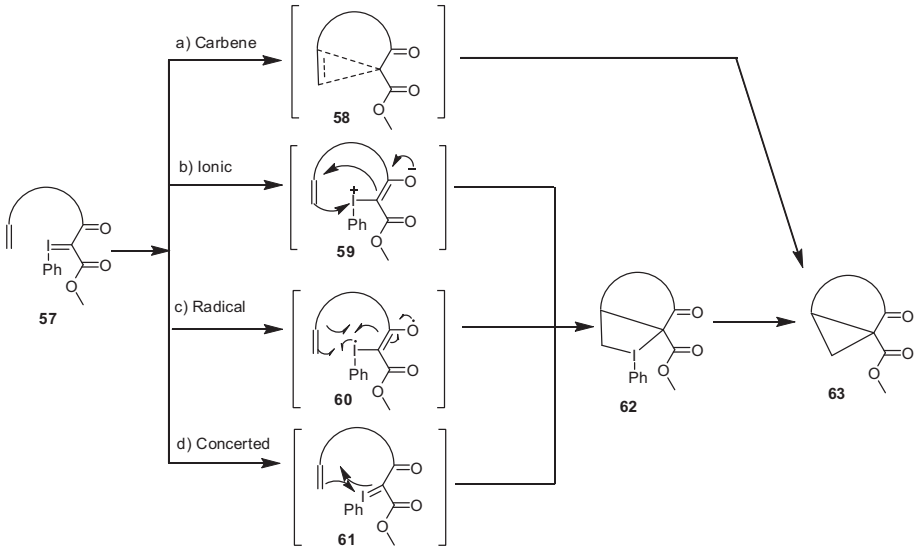


Figure 6.

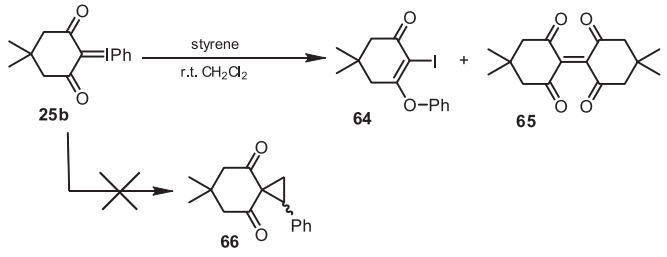
2.2. Mechanism of metal-free intramolecular cyclopropanation

Theoretically there are four possible routes for metal-free intramolecular cyclopropanation: (a) carbene, (b) ionic, (c) radical, and (d) concerted (Scheme 10). The reaction may involve a four-membered iodocyle **62** that can be formed via ionic **59**, radical **60**, or in a sigmatropic fashion **61**. Another possibility is that the reaction may involve iodonium ylides, involves formation of reactive copper-carbenoids.[46] A similar kind of reactivity is expected if non-metal reactions proceed via a free carbene intermediate. Camacho et al. showed that the dissociation of iodine–carbon bond to generate a free carbene has a high activation energy and occurs only at elevated temperatures.[41] When the intermolecular cyclopropanation of iodonium ylides generated from dimedone and various alkenes (cyclohexene, styrene, etc.) was attempted, only 1,4-phenyl migration **64** along with dimerization of



Scheme 10.

ylide **65** was observed (Scheme 11). Only intramolecular reactions with fixed carbon chain length afforded cyclopropanation in good yields (Table 3). However, when the same reaction was carried out in the presence of Rh(II), substituted cyclopropane **66** (Scheme 11) was obtained in very good yields.



Scheme 11.

Based on the above observations, the probability of involvement of the free carbene intermediate is highly unlikely.

2.2.2. Ionic pathway. The second possibility is that reaction may be occurring via a stepwise ionic route. The metal-free cyclopropanation of ylides 4**6a**–**e** was carried out in a variety of solvents including THF, DCM, chloroform, DMF, acetonitrile, etc., and there was no significant effect of the polarity of the solvent on either the yields of product or the rate. An ionic pathway would involve the nucleophilic attack of the double bond on the electron deficient iodine atom along with formation of carbocation. It is well known that rate of alkyl and hydride shifts in bicyclic systems is faster than other reactions.[47] However, in the case of phenylidonium ylide **57**, none of expected Wagner–Meerwein rearrangement products was observed.[48] Also, we didn't observe any [3+2] cycloaddition product, which potentially could result from the zwitterionic form of ylides. These observations strongly suggest the absence of ionic pathway.

2.2.3. Radical pathway. The third possibility is that the reaction may involve free radicals that could be generated by homolytic cleavage of the carbon–iodine double bond with visible light. To check the affect of light on the reaction, we conducted the cyclopropanation in the dark, but the reaction proceeded with same ease as it did under visible light. Also, the ESR spectrum of phenyliodonium ylides failed to show any signal to indicate the presence of unpaired electrons, even at high temperatures. Signals could only be obtained when these iodonium ylides were heated with hydrogen peroxide. Again, the absence of any rearranged products that could possibly arise from a rearrangement of free radicals indicates that reaction may not involve free radical intermediates.

2.2.4. Sigmatropic pathway. Although, there is now no concrete mechanistic proof available to show that the reaction is sigmatropic in nature, conformational rigidity (entropy) appears to be playing an important role in the reaction. When substrates with a double bond one carbon away or closer to the reaction center were attempted, the reaction failed to provide cyclopropanes, and only dimers or phenyl migration products were obtained. It is plausible to assume that the reaction may be proceeding through a well organized transition state. Taking into account all of the above observations, it is likely that a concerted [2+2] cycloaddition of the alkene to the carbon–iodine double bond, to form a four-membered iodocyle followed by reductive elimination of iodobenzene is likely to be actual mechanism. Four-membered iodocyles have also been reported in literature.[49]

3. Conclusion

Cyclopropanes are very valuable to organic chemists and offer an exploitable synthon for the construction a variety of biologically active compounds. We have productively pursued a metal-free, environmentally friendly route for the synthesis of cyclopropanes and the reaction mechanism was studied in detail using various control experiments. A salient feature of the non-metal route is that it works efficiently for conformationally rigid systems. Out of many possible reaction pathways, a carbene pathway is categorically ruled out. A more detailed study of the mechanism is a work in progress in our lab that involves DFT calculations and optimization studies to further develop a stereoselective non-metal route for the synthesis of cyclopropanes. Undoubtedly, these results open a path for the less stable, but often more reactive, chloronium and bromonium ylides to develop intermolecular metal-free cyclopropanation.

4. Experimental section

4.1. General

NMR spectra were recorded on a Bruker Avance DRX-500 (500 MHz) or DPX-400 (400 MHz) instrument at 25 °C. Column

chromatography was carried out using Silicycle Silica-P Flash silica gel (40–63 μm). Pre-coated silica gel plates F-254 were used for thin-layer analytical chromatography. All reactions were done under positive pressure of argon unless otherwise stated. Acetonitrile was dried by refluxing over calcium hydride; dichloromethane was dried by refluxing over CaH_2. NMR solvents (Cambridge Isotopes Laboratories) were used without purification. Melting points were recorded on a Fisher Johns apparatus and are uncorrected. FTIR spectra were recorded using thin film over KBr pellets on a Varian 1000 FTIR instrument at 25 °C. LRMS (ESI) of all new compounds were recorded on a Thermo-Finnigan LTQ FT spectrometer and (FAB) LRMS was recorded on JEOL GCMATE II spectrometer.

4.2. Preparation of acid chlorides

Acid chlorides were prepared by using Scheme 8 or by using known literature procedures.[50,51] Separation of *endo* and *exo*-isomer was done by the reported procedures.[48]

*4.2.1. 5-Iodo-bicyclo[2.2.1]hept-5-ene-2-lactone (**52a**).* To the mixture of *endo* and *exo*-norbornenecarboxylic acid (Scheme 8) 3 g (21 mmol) in 64 mL of 5% aqueous $NaHCO_3$ solution were added 6 g (27 mmol) of iodine and 11 g (67 mmol) of potassium iodide. The resulting dark brown mixture was stirred overnight at room temperature. The reaction mixture was extracted with chloroform (100 mL×5). The organic layer was washed with aqueous $NaHCO_3$ solution and with aqueous sodium thiosulfate solution to remove the excess iodine. Sodium salt of *exo*-isomer was removed by washing organic layer with $NaHCO_3$ and water. The colorless organic layer was then washed with brine and dried over anhydrous sodium sulfate. The organic layer was concentrated and iodolactone was purified using column chromatography to obtain 4.75 g of iodolactone **52a** as colorless oil (2:8, EtOAc/hexanes) (83%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.12 (s, 1H), 3.88 (s, 1H), 3.19 (s, 1H), 2.72 (s, 1H), 2.57 (dd, J=7.1, 3.9 Hz, 1H), 2.37 (d, J=9.9 Hz, 1H), 2.07 (ddd, J=13.6, 11.3, 3.9 Hz, 1H), 1.94–1.73 (m, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 179.7, 89.4, 47.2, 47.0, 37.8, 37.9, 34.9, 30.2. ESI (LRMS): M+Na: 287.12.

*4.2.2. Bicyclo[2.2.1]hept-5-ene-2-carboxylic acid (**54a**).* To the solution of 4.7 g (17 mmol) iodolactone **52** in 30 mL of anhydrous methanol, 1.74 g (27 mmol) of activated zinc powder was added. The resulting suspension was stirred for 3 h at room temperature. The reaction mixture was filtered over Celite and solvent was concentrated. To the residue 30 mL of 1:1 mixture of dichloromethane and water was added and the mixture was acidified to pH=2 using aqueous HCl followed by extraction with dichloromethane (20 mL×3). The organic layer was washed with water and brine and dried over anhydrous Na_2SO_4. After removal of solvent, 1.89 g of foul smelling, colorless oil was obtained (77%). ESI (LRMS): M+Na: 161.08.

*4.2.3. Bicyclo[2.2.1]hept-5-ene-2-carbonyl chloride (**55a**).* A solution of 2.57 g (17 mmol) *endo* 5-norbornene-2-carboxylic acid in 20 mL of thionyl chloride was stirred at 60 °C for 1 h. After removal of excess thionyl chloride under reduced pressure, the crude product was obtained in 85% yield and was used for next reaction without further purification.

*4.2.4. Bicyclo[2.2.2]oct-5-ene-2-carbonyl chloride (**55b**).* To the 1.3 g (17 mmol) of cyclohexadiene were added 0.5 g (5.6 mmol) of acryloyl chloride and catalytic amount of propylene oxide and reaction mixture was stirred at room temperature for 24 h in dark. Excess cyclohexadiene was removed under reduced pressure. The crude ^{1}H NMR showed quantitative conversion with *endo* isomer as major product. Separation of *endo* and *exo*-isomer was done using same procedure as for 5-norbornene-2-carboxylic acid. ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.31 (s, 1H), 4.25 (dd, J=3.9, 2.1 Hz, 1H), 3.72 (s, 3H), 3.09 (d, J=5.5 Hz, 1H), 2.63 (ddd, J=11.2, 5.8, 2.1 Hz, 1H), 2.24 (ddt, J=13.9, 5.8, 2.9 Hz, 1H), 2.17 (dd, J=5.8, 2.9 Hz, 1H), 2.04–1.87 (m, 3H), 1.79–1.69 (m, 1H), 1.69–1.58 (m, 2H), 1.58–1.47 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 178.02, 81.89, 52.69, 39.49, 38.31, 35.62, 35.39, 29.37, 24.46, 21.28.

4.3. Preparation of β-ketoesters[52]

All β-ketoesters were prepared by using following representative procedure.

*4.3.1. Methyl-3-(bicyclo[2.2.1]hept-5-en-2-yl)-3-oxopropanoate (**56a**).* To the solution of 2.79 g (17.4 mmol) of Meldrum's acid in 11.8 mL of dry pyridine and 25 mL of dry dichloromethane at 0 °C was slowly added the solution of above acid chloride in 30 mL of dry dichloromethane. Stirring was continued for 2 h at room temperature. The resulting blood red colored reaction mixture was diluted with 50 mL of dichloromethane and was washed with 4 N HCl followed by water and brine. After drying over anhydrous Na_2SO_4, the solvent was removed under reduced pressure and the residue was refluxed in dry methanol for 8 h. The crude β-ketoester **56a** was purified using flash column chromatography using 1:9 EtOAc/hexanes mixture to yield 1.8 g of colorless oil (60% over two steps). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.77–5.72 (m, 1H), 5.59–5.50 (m, 1H), 3.76 (s, 3H), 3.48 (s, 2H), 2.72–2.65 (m, 1H), 2.57–2.53 (m, 2H), 1.95–1.93 (m, 2H), 1.88–1.86 (m, 1H), 1.72–1.70 (m, 1H), 1.53–1.45 (m, 1H), 1.36–1.28 (m, 1H), 1.28–1.20 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 198.8, 168.25, 130.6, 128.2, 52.5, 49.2, 32.1, 29.5, 28.0, 24.1, 21.7. IR: ν_{max} (neat)/cm^{-1} (KBr) 3019, 2977, 2844, 1747, 1716, 1649, 1628, 1406, 1317, 993. ESI (LRMS): M+Na: 217.17.

*4.3.2. Methyl-3-(bicyclo[2.2.2]oct-5-en-2-yl)-3-oxopropanoate (**56b**).* The crude β-ketoester was purified using flash column chromatography using 1:9 EtOAc/hexanes mixture to yield 0.65 g of colorless oil (80% over two steps). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.30–6.24 (m, 1H), 6.08 (t, J=7.3 Hz, 1H), 3.70 (s, 3H), 3.45 (s, 2H), 2.92–2.85 (m, 1H), 2.85–2.76 (m, 1H), 2.60 (dt, J=6.5, 2.8 Hz, 1H), 1.68–1.62 (m, 2H), 1.62–1.55 (m, 1H), 1.53–1.45 (m, 1H), 1.36–1.28 (m, 1H), 1.28–1.20 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 203.8, 168.2, 135.7, 131.2, 51.5, 47.6, 32.2, 29.8, 28.9, 26.1, 24.7. IR: ν_{max} (neat)/cm^{-1} (KBr) 3061, 2944, 2865, 1749, 1710, 1653, 1623, 1436, 1324, 1261, 1151, 1091. ESI (LRMS): M+Na: 231.24.

*4.3.3. Methyl-3-(cyclohex-3-enyl)-3-oxopropanoate (**56c**).* The crude β-ketoester was purified using flash column chromatography using 1:9 EtOAc/hexanes mixture to yield 1.7 g of colorless oil (68% over two steps). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74–5.65 (m, 2H), 3.73 (s, 3H), 3.54 (s, 2H), 2.85–2.58 (m, 1H), 2.31–2.24 (m, 1H), 2.18 (dt, J=3.7, 2.4 Hz, 1H), 2.10 (tdd, J=14.3, 8.5, 5.9 Hz, 2H), 2.03–1.94 (m, 1H), 1.58 (dddd, J=13.0, 11.3, 9.5, 6.6 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 205.8, 168.2, 127.1, 125.4, 125.3, 52.7, 47.5, 47.2, 26.9, 25.2, 24.9, 24.7. IR: ν_{max} (neat)/cm^{-1} (KBr) 3052, 2952, 2850, 1749, 1716, 1650, 1627, 1436, 1405, 1322, 1241, 1153, 1006. ESI (LRMS): M+Na: 205.17.

*4.3.4. Methyl-3-(3-methylcyclohex-3-enyl)-3-oxopropanoate (**56d**).* The crude β-ketoester was purified using flash column chromatography using 2:8 EtOAc/hexanes mixture to yield 0.81 g of colorless oil (71.2% over two steps). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.47–5.33 (m, 1H), 3.75 (s, 3H), 3.55 (s, 2H), 2.67 (dddd, J=11.2, 8.7, 6.4, 2.5 Hz, 1H), 2.29–2.15 (m, 2H), 2.12–1.92 (m, 3H), 1.73–1.52 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 205.9, 168.2, 134.3, 119.3, 52.7, 47.6, 47.2, 29.7, 27.3, 25.1, 23.7. IR: ν_{max} (neat)/cm^{-1} (KBr) 3044,

2927, 2838, 1749, 1710, 1652, 1623, 1438, 1322, 1234, 1155, 1022. ESI (LRMS): M+Na: 219.17.

*4.3.5. Methyl-3-(3,4-dimethylcyclohex-3-enyl)-3-oxopropanoate (**56e**).* The crude β-ketoester was purified using flash column chromatography using 1:9 EtOAc/hexanes mixture to yield .65 g of colorless oil (80% over two steps). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.76 (s, 3H), 3.55 (s, 2H), 2.71 (dddd, J=11.4, 10.3, 5.3, 2.9 Hz, 1H), 2.28–2.14 (m, 1H), 2.13–2.00 (m, 3H), 2.00–1.92 (m, 1H), 1.65 (s, 3H), 1.60 (s, 3H), 1.61–1.51 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 205.8, 168.2, 125.8, 124.1, 52.7, 48.2, 47.6, 33.2, 31.4, 25.5, 19.4, 19.2. IR: ν_{max} (neat)/cm^{-1} (KBr) 3052, 2952, 2850, 1749, 1716, 1650, 1627, 1436, 1405, 1322, 1241, 1153, 1006. ESI (LRMS): M+Na: 233.24.

*4.3.6. Methyl-4-(cyclopent-2-enyl)-3-oxobutanoate (**56f**).* The crude β-ketoester was purified using flash column chromatography using 1:9 EtOAc/hexanes mixture to yield 0.65 g of colorless oil (60% over two steps). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74 (ddd, J=5.5, 4.4, 2.2 Hz, 1H), 5.62 (dq, J=5.6, 2.1 Hz, 1H), 3.72 (s, 3H), 3.44 (s, 2H), 3.09 (dtdd, J=8.4, 6.5, 4.3, 2.1 Hz, 1H), 2.58 (qd, J=17.1, 7.2 Hz, 2H), 2.37–2.24 (m, 2H), 2.19–2.06 (m, 1H), 1.36 (ddt, J=12.8, 8.8, 6.3 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 202.6, 168.0, 133.9, 131.9, 89.8, 52.7, 49.7, 49.5, 41.0, 32.2, 30.1. IR: ν_{max} (neat)/cm^{-1} (KBr) 3052, 2952, 2850, 1749, 1716, 1650, 1627, 1436, 1405, 1322, 1241, 1153, 1006. ESI (LRMS): M+Na: 205.22.

4.4. Preparation of phenyliodonium ylides

Phenyliodonium ylides were prepared by using modified schank's procedure. To the solution of 1.2 g (21 mmol) in 15 mL of methanol was added a solution of β-ketoester 1.17 g (7 mmol) in 5 mL of dry methanol at −10 °C at a rate so that internal temperature did not rise above 0 °C. The turbid reaction mixture was stirred at same temperature for 20 min before addition of 1.94 g (7 mmol) solid IBD in one portion. The reaction mixture was stirred for 2 h at 0 °C in dark. A white solid precipitated from the yellow mother liquor. The reaction was quenched with ice/water mixture (Sometimes precipitation occurs after addition of ice/water mixture.). The solid was filtered and dried in dark and crystallized using DCM/hexanes mixture.

*4.4.1. Methyl-3-(bicyclo[2.2.1]hept-5-en-2-yl)-2-phenyliodonio-3-oxopropanoate (**51a**)*[28]. White solid (80%). Mp 98–100 °C (dec). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79–7.70 (m, 2H), 7.57–7.48 (m, 1H), 7.44–7.35 (m, 2H), 6.20 (dd, J=5.6, 3.1 Hz, 1H), 5.80 (dd, J=5.6, 2.8 Hz, 1H), 4.25–4.15 (m, 1H), 3.69 (s, 3H), 3.30 (s, 1H), 2.89 (s, 1H), 1.89 (ddd, J=11.4, 9.1, 3.7 Hz, 1H), 1.69–1.52 (m, 1H), 1.47–1.32 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.4, 137.5, 133.1, 132.5, 131.8, 131.5, 51.9, 50.5, 47.7, 45.7, 43.5, 30.5, 25.6. IR: ν_{max} (neat)/cm^{-1} (KBr) 3054, 2966, 2863, 1641, 1563, 1471, 1430, 1363, 1336, 1299, 1270, 1182, 1064, 1041. FAB (LRMS): M+H: 397.22.

*4.4.2. Methyl-3-(bicyclo[2.2.2]oct-5-en-2-yl)-2-phenyliodonio-3-oxopropanoate (**51b**).* Highly unstable pale yellow gummy solid immediately started decomposing at room temperature to give oil (69%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.72 (d, J=7.3 Hz, 1H), 7.51 (t, J=6.8 Hz, 1H), 7.38 (t, J=7.6 Hz, 1H), 6.30 (t, J=7.3 Hz, 1H), 6.16 (t, J=7.0 Hz, 1H), 4.00–3.89 (m, 1H), 3.65 (s, 2H), 2.79 (s, 1H), 2.57 (s, 1H), 1.84 (t, J=11.0 Hz, 1H), 1.74 (d, J=10.9 Hz, 1H), 1.67 (s, 1H), 1.59–1.50 (m, 1H), 1.26 (s, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 164.8, 133.9, 132.7, 132.2, 131.3, 131.0, 51.4, 44.2, 34.4, 31.8, 30.1, 26.5, 24.2. IR: ν_{max} (neat)/cm^{-1} (KBr) 2993, 2974, 1659, 1556, 1532, 1456, 1416, 1357, 1305, 1269, 1147, 1079, 1031.

*4.4.3. Methyl-3-(cyclohex-3-enyl)-2-phenyliodonio-3-oxopropanoate (**51c**).* Pale yellow solid (83%). Mp 115–116 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.75 (dt, J=3.0, 1.7 Hz, 2H), 7.55–7.49 (m, 1H), 7.42–7.35 (m, 2H), 5.76–5.70 (m, 1H), 5.70–5.65 (m, 1H), 3.93 (tdd, J=11.5, 5.0, 2.7 Hz, 1H), 3.65 (s, 3H), 2.34–2.25 (m, 1H), 2.24–2.05 (m, 2H), 1.94–1.86 (m, 1H), 1.68 (ddd, J=24.0, 11.5, 5.5 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 192.7, 132.8, 131.4, 131.2, 126.6, 126.4, 109.6, 51.6, 40.6, 28.8, 26.9, 25.6. IR: ν_{max} (neat)/cm^{-1} (KBr) 2982, 2933, 1648, 1567, 1542, 1461, 1423, 1368, 1316, 1280, 1174, 1089, 1024. FAB (LRMS): M+H: 385.12.

*4.4.4. Methyl-3-(3-methylcyclohex-3-enyl)-2-phenyliodonio-3-oxopropanoate (**51d**).* Pale yellow solid (75%). Mp 96–97. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81–7.71 (m, 2H), 7.53 (t, J=7.4 Hz, 1H), 7.47–7.36 (m, 2H), 5.43 (s, 1H), 3.86 (tdd, J=19.3, 9.6, 7.1 Hz, 1H), 3.66 (s, 3H), 2.31–2.20 (m, 1H), 2.19–2.07 (m, 2H), 2.06–1.86 (m, 2H), 1.79–1.70 (m, 2H), 1.66 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.5, 165.3, 133.8, 133.2, 131.9, 131.6, 121.0, 112.8, 52.1, 41.1, 30.9, 29.5, 27.7, 24.0. IR: ν_{max} (neat)/cm^{-1} (KBr) 2942, 2913, 1658, 1563, 1548, 1469, 1432, 1375, 1336, 1284, 1182, 1079, 1054. FAB (LRMS): M+H: 399.24.

*4.4.5. Methyl-3-(3,4-dimethylcyclohex-3-enyl)-2-phenyliodonio-3-oxopropanoate (**51e**).* Unstable yellow gummy solid (60%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.76 (d, J=7.6 Hz, 1H), 7.52 (t, J=7.4 Hz, 1H), 7.38 (t, J=7.8 Hz, 1H), 3.89 (tdd, J=11.5, 5.0, 2.7 Hz, 1H), 3.64 (s, 2H), 2.34–2.20 (m, 1H), 2.17 (s, 1H), 1.98 (dd, J=37.5, 14.4 Hz, 2H), 1.85 (dd, J=7.5, 5.1 Hz, 1H), 1.70–1.55 (m, 5H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 168.2, 135.8, 131.4, 131.1, 130.5, 125.0, 119.9, 74.7, 51.5, 43.5, 35.1, 32.1, 31.5, 27.7, 22.6, 19.0, 18.8. IR: ν_{max} (neat)/cm^{-1} (KBr) 2917, 2854, 1658, 1548, 1471, 1432, 1373, 1340, 1288, 1182, 1054, 1012.

*4.4.6. Methyl-4-(cyclopent-2-enyl)-2-phenyliodonio-3-oxobutanoate (**43**)*[28]. White solid (93%). Mp 119–120 °C (dec). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.77 (dt, J=2.9, 1.7 Hz, 1H), 7.56–7.48 (m, 1H), 7.45–7.33 (m, 1H), 5.76–5.66 (m, 1H), 3.65 (s, 2H), 3.24–3.14 (m, 1H), 3.06 (d, J=7.3 Hz, 1H), 2.36 (dddd, J=16.6, 9.0, 5.0, 2.7 Hz, 1H), 2.31–2.20 (m, 1H), 2.13–1.98 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 188.8, 165.2, 135.2, 132.8, 131.4, 131.2, 130.2, 112.5, 51.6, 43.5, 43.2, 31.8, 29.7. IR: ν_{max} (neat)/cm^{-1} (KBr) 2977, 2854, 1662, 1554, 1484, 1432, 1377, 1363, 1279, 1172, 1066. FAB (LRMS): M+H: 385.06.

4.5. Intramolecular metal-free cyclopropanation of unsaturated phenyliodonium ylides

Intramolecular metal-free cyclopropnation was achieved by using following general procedure: 50 mg of phenyliodonium ylide was dissolved in 3 mL dry DCM under argon to obtain a dark yellow color solution. The reaction mixture was stirred at room temperature till the solution became colorless (3 h). Solvent was evaporated and product was purified using flash column chromatography 25:75 (EtOAc/hexanes).

*4.5.1. 1,3-Methanocyclopropa-pentalene-2α(2H)-carboxylic acid, hexahydro-2-oxo-, methyl ester (**46a**)*[29]. Oil (95%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.74 (s, 3H), 3.10 (dd, J=7.5, 4.2 Hz, 1H), 2.86–2.77 (m, 2H), 2.64 (s, 1H), 2.46 (dd, J=8.5, 5.0 Hz, 1H), 2.06 (d, J=9.1 Hz, 1H), 1.90–1.70 (m, 1H), 1.60–1.51 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 167.3, 52.6, 50.3, 47.5, 46.3, 46.0, 44.5, 42.6, 37.7, 36.7. IR: ν_{max} (neat)/cm^{-1} (KBr) 2933, 2821, 1760, 1732, 1654, 1431, 1342, 1259, 1222, 1080. ESI (LRMS): M+Na: 215.23.

*4.5.2. 1,3-Methanocyclopropa-hexalene-2α(2H)-carboxylic acid, hexahydro-2-oxo-, methyl ester (**46b**).* Oil (55%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.78 (s, 3H), 2.74–2.66 (m, 2H), 2.53–2.38 (m, 1H), 2.32–2.20 (m, 2H), 1.88 (ddd, J=13.4, 6.1, 1.9 Hz, 1H), 1.80–1.61 (m, 5H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 206.1, 169.1, 52.6, 45.7, 40.8, 37.5, 36.7, 34.9, 27.3, 27.1, 23.1, 18.2. IR: ν_{max} (neat)/cm^{-1} (KBr) 2933,

2821, 1760, 1732, 1654, 1431, 1342, 1259, 1222, 1080. ESI (LRMS): M+Na: 229.10.

*4.5.3. 1,3-Methanocyclopropa-2α(2H)-carboxylic acid, hexahydro-2-oxo-, methyl ester (**46c**).* Oil (80%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.76 (s, 3H), 2.83 (dd, J=7.8, 3.7 Hz, 1H), 2.63 (d, J=7.9 Hz, 2H), 2.32–2.21 (m, 2H), 2.16–2.06 (m, 2H), 2.05–1.83 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 208.1, 168.8, 53.4, 52.2, 42.9, 39.6, 37.4, 29.8, 26.3, 16.3. IR: ν_{max} (neat)/cm^{-1} (KBr) 2948, 2871, 1756, 1733, 1716, 1436, 1348, 1257, 1213, 1078. ESI (LRMS): M+Na: 203.10.

*4.5.4. 1,3-Methanocyclopropa-1-Methyl-2α(2H)-carboxylic acid, hexahydro-2-oxo-, methyl ester (**46d**).* Oil (68%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.81 (s, 3H), 2.67 (d, J=3.9 Hz, 1H), 2.36–2.24 (m, 1H), 2.12–2.03 (m, 1H), 1.98 (dddd, J=12.9, 10.4, 5.6, 3.0 Hz, 1H), 1.94–1.82 (m, 2H), 1.65 (t, J=12.8 Hz, 2H), 1.24 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 52.6, 46.5, 42.1, 38.6, 29.7, 28.7, 27.4, 24.2, 20.8. IR: ν_{max} (neat)/cm^{-1} (KBr) 2940, 2868, 1749, 1737, 1709, 1432, 1353, 1249, 1231, 1070. ESI (LRMS): M+Na: 217.21.

*4.5.5. 1,3-Methanocyclopropa-1,3-Dimethyl-2α(2H)-carboxylic acid, hexahydro-2-oxo-, methyl ester (**46e**).* Oil (54%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.77 (s, 3H), 2.27–2.20 (m, 1H), 2.18–2.06 (m, 1H), 2.03–1.89 (m, 3H), 1.89–1.79 (m, 2H), 1.44 (s, 3H), 1.20 (s, 3H). ^{13}C NMR (126 MHz, C_6D_6) δ 205.8, 168.2, 51.9, 42.6, 42.1, 34.7, 28.8, 24.5, 17.5, 15.4. IR: ν_{max} (neat)/cm^{-1} (KBr) 2944, 2869, 1758, 1735, 1436, 1390, 1334, 1315, 1255, 1216, 1087. ESI (LRMS): M+Na: 230.94.

*4.5.6. Cyclopropa-pentalene-2α(2H)-carboxylic acid, hexahydro-2-oxo-, methyl ester (**46**)*[29]. Oil (95%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.72 (s, 1H), 3.21–3.14 (m, 1H), 2.96–2.87 (m, 1H), 2.78–2.62 (m, 1H), 2.23–2.03 (m, 1H), 1.89 (d, J=17.4 Hz, 1H), 1.76–1.64 (m, 1H), 1.54 (dd, J=11.9, 6.4 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 167.90, 94.32, 52.28, 49.41, 46.95, 45.78, 40.68, 40.05, 36.01, 24.76. IR: ν_{max} (neat)/cm^{-1} (KBr) 2960, 2841, 1754, 1738, 1435, 1349, 1259, 1231, 1094, 1012. ESI (LRMS): M+Na: 203.19.

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Supplementary data

Structural proofs and spectral data for all new compounds are provided. Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2010.05.005. These data include MOL files and InChIKeys of the most important compounds described in this article.

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