Highly Effective Catalytic Methods for Ylide Generation from Diazo Compounds. Mechanism of the Rhodium- and Copper-Catalyzed Reactions with Allylic Compounds

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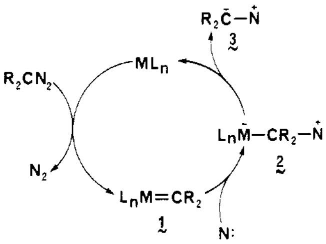
The catalytic effectiveness of rhodium(II) acetate and hexadecacarbonylhexarhodium for ylide generation in reactions of diazo compounds with allyl methyl sulfide, representative allylic tertiary amines, and allyl halides is described. Exclusive formation of products derived from the [2,3] sigmatropic rearrangement of ylide intermediates generated from ethyl diazoacetate and allyl sulfides, amines, or iodides is observed. Cyclopropanation is dominant in reactions of either diethyl diazomalonate or ethyl diazoacetate with allyl chloride, and competition between cyclopropanation and ylide rearrangement is exhibited in reactions with allyl bromide. Allyl iodide and allyl methyl sulfide are very similar in their ability to intercept the presumed carbenoid intermediates. Copper catalysis results in significantly higher yields of ylide-derived products, relative to cyclopropane products, than does rhodium catalysis in reactions with allyl bromides and chlorides. Reactions with crotyl bromide further exemplify the catalytic dissimilarities of rhodium and copper compounds and identify alternative transformations of metal-associated ylide intermediates. Cyclopropanation and metal ylide formation are represented as competing processes. Metal dissociation from the metal-associated ylide intermediate produces a reactive allylic ylide that is subject to the [2,3] sigmatropic rearrangement. However, products derived from rearrangement of the metal-associated ylide by allyl group transfer to the metal are observed to predominate in copper-catalyzed reactions of ethyl diazoacetate with crotyl bromide. These same products are not observed in rhodium(II) acetate catalyzed reactions performed at or below 25 °C.

Carbenoid entry into reactive ylides represents a useful alternative to the widely employed base-promoted methodologies.[1-9] Although suitable for ylide production, carbenes generated photochemically and thermally in the presence of organic compounds containing heteroatoms are relatively indiscriminate.[10,11] Dichlorocarbene has been advantageously employed for ylide transformations with allylic sulfides,[12,13] but extensions of this methodology are limited. The potentially more general catalytic approach to carbenoid generation has begun to evolve with the use of copper catalysts;[14-20] however, because of the nature and extent of competing carbenoid reactions and catalyst inhibition from organic compounds containing heteroatoms, the general applicability of this method has been restricted to reactions with divalent sulfur compounds. Recently, stable thiophene sulfur ylides have been generated by rhodium(II) acetate catalyzed decomposition of diazomalonate,[21] but, as has been the case with the copper-catalyzed transformations, the broad versatility of ylide generation by this catalytic methodology has not been established.

Scheme I



Ylide generation is consistent with the formation of reactive electrophilic metal carbene intermediates. Stable metal carbenes characteristically undergo nucleophilic addition at the carbene carbon, and stable addition products (2) have been obtained from the reactions of tertiary amines and phosphines with carbene complexes[22,23] (eq 1). Entry to 2 has also been achieved through reactions of transition-metal compounds with ylides,[24,25] and the reverse transformations of 2 to either 3[26] or 1[27-29] have

$$\mathrm{N{:}} + \underset{1}{\mathrm{L}_n\mathrm{M{=}CR_2}} \rightleftharpoons \underset{2}{\mathrm{L}_n\mathrm{M^-{-}CR_2{-}N^+}} \rightleftharpoons \mathrm{L}_n\mathrm{M} + \underset{3}{\mathrm{R_2C^-{-}N^+}} \quad (1)$$

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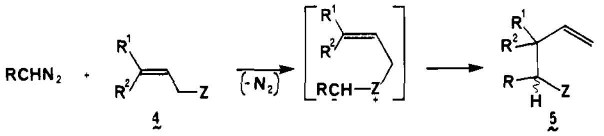
Table I. Product Yields from Hexadecacarbonylhexarhodium and Rhodium(II) Acetate Catalyzed Reactions of Ethyl Diazoacetate with Allyl Sulfides and Amines[a]

Z	R^1	R^2	catalyst (mol %)[b]	product	yield,[c] %
SMe	H	H	$Rh_6(CO)_{16}$ (0.5)	**5a**	96
			$Rh_2(OAc)_4$ (0.5)	**5a**	91
NMe_2	H	H	$Rh_6(CO)_{16}$ (0.5)	**5b**	82
			$Rh_2(OAc)_4$ (1.0)	**5b**	60
NMe_2	CH_3	CH_3	$Rh_6(CO)_{16}$ (0.4)	**5c**	49
			$Rh_2(OAc)_4$ (1.0)	**5c**	37
NMe_2	CH_3	H	$Rh_6(CO)_{16}$ (0.2)	**5d**	36 (77:23)
			$Rh_2(OAc)_4$ (0.5)	**5d**	79 (75:25)
NMe_2	C_6H_5	H	$Rh_6(CO)_{16}$ (0.5)	**5e**	78 (72:28)
			$Rh_2(OAc)_4$ (0.5)	**5e**	59 (75:25)

[a] Reactions were performed at 60 °C under an inert atmosphere. [b] Based on ethyl diazoacetate. [c] Isolated product yield (ratio of diastereomers given in parentheses).

been reported. In the catalytic approach to ylide generation, suitable reactants, typically diazo compounds, are considered to combine with the transition-metal catalyst to form a reactive electrophilic carbene complex following nitrogen expulsion. Nucleophilic addition followed by dissociation of the catalytically active metal species and ylide complete the catalytic cycle (Scheme I).

The symmetry-allowed [2,3] sigmatropic rearrangement[30] is widely recognized as a facile bond reorganization process, particularly for allylic nitrogen and sulfur ylides. This rearrangement process effectively entraps the initially formed allylic ylide intermediate formed by catalytic decomposition of diazo compounds in the presence of allylic substrates (eq 2). The effectiveness of ylide entrapment



(2)

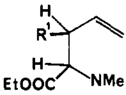
of the carbenoid intermediate can be determined by competition between [2,3] sigmatropic rearrangement of the generated ylide and cyclopropanation of the carbon–carbon double bond.[31] In addition, these processes provide a probe for understanding the nature of the catalytically active metal species and, as we now report, identify alternate transformations of metal-associated ylide intermediates (2).

Results

Allyl Sulfonium and Ammonium Ylides. Table I records results obtained from reactions of ethyl diazoacetate with allyl methyl sulfide and representative allylic tertiary amines that are catalyzed by $Rh_6(CO)_{16}$ and $Rh_2(OAc)_4$. As has been previously observed with the use of copper catalysts,[17b] the rhodium-catalyzed reactions of ethyl diazoacetate with allyl methyl sulfide are remarkably specific and provide the formal C–S insertion product **5** in nearly quantitative yield. However, rhodium-catalyzed reactions of ethyl diazoacetate with allylamines indicate the unique advantages of these catalysts:[32] moderate temperatures are employed for these transformations, ylide rearrangement occurs without observable cyclopropanation or Stevens [1,2] rearrangement, and products derived from the [2,3] sigmatropic rearrangement of presumed intermediate ylides are obtained in moderate to high yields. In contrast, only low to moderate yields of the ylide rearrangement products analogous to **5b** and **5c** were obtained when diazomalonate, which is more susceptible to catalytic ylide generation than is ethyl diazoacetate, was employed in copper chloride catalyzed reactions at a temperature of 110 °C.[17a]

In contrast to the thermal and photochemical processes, in which cyclopropanation competes with ylide generation,[17a] the only detectable process in competition with the production of **5** in the rhodium-catalyzed reactions is the formation of diethyl maleate and diethyl fumarate. As would be expected from such a competitive process,[33] increasing the initial concentration of the allylic substrate relative to that of ethyl diazoacetate results in increased yields of the ylide rearrangement products. For example, the yield of **5a** increases from 46% to 77% when the molar ratio [**4a**]/[EDA] is changed from 1.2 to 2.0 in reactions catalyzed by $Rh_2(OAc)_4$. Similarly, the $Rh_2(OAc)_4$-catalyzed reactions, the yield of **5b** increases in the order 30%, 44%, 59% with the use of [**4b**]/[EDA] molar ratios of 1.4, 2.8, and 5.0. Optimum yields of **5** (Table I) are obtained when [**4**]/[EDA] is between 5 and 10.

Two diastereoisomeric products are obtained from the rhodium-catalyzed reactions of ethyl diazoacetate with tertiary amines **5d** and **5e** and are assigned structures A and B on the basis of their NMR spectra. As described



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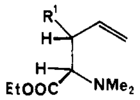

B

in Table I, one diastereoisomer (**5d**, $R^1 = CH_3$; **5e**, $R^1 = C_6H_5$) is formed with a moderate degree of selectivity in each of these transformations, and the selectivities achieved are nearly identical with those recently reported for base-promoted reactions of the analogous but-2-enyldimethylphenacylammonium and cinnamyldimethylphenacylammonium bromides.[8b] Although configurational assignments of the dominant diastereoisomers are not firmly established, spectral comparisons of compounds **5d,e** with those from the analogous base-promoted reactions[8b] do specify that the major isomers from the catalytic transformations are the same as those produced in the base-promoted processes. The comparative stereoselectivities achieved in these transformations are those expected from the symmetry-allowed [2,3] sigmatropic rearrangement and suggest that the catalyst is not involved in the rearrangement process.

The reaction temperatures required for ylide formation from allyl sulfides and allyldimethylamines are significantly higher than those normally employed for cyclopropanation of alkenes and vinyl ethers.[33,34] As both rhodium(II) acetate[35] and the hexarhodium carbonyl cluster[36] react with sulfur and nitrogen compounds to form stable adducts or substitution products, their decreased activity can be attributed to competitive coordination

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Table II. Products and Product Yields from $Rh_6(CO)_{16}$- and $Rh_2(OAc)_4$-Catalyzed Reactions of Ethyl Diazoacetate with Allyl Halides[a]

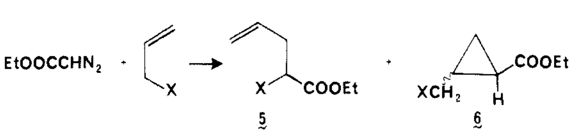
allyl halide	catalyst	% yield[b] of 5 + 6	ratio of 5/6 (trans/cis)[c]
H_2C=$CHCH_2I$	$Rh_6(CO)_{16}$	89	100:0
	$Rh_2(OAc)_4$	98	100:0
H_2C=$CHCH_2Br$	$Rh_6(CO)_{16}$	41	27:73 (1.13)
	$Rh_2(OAc)_4$	76	28:72 (1.12)
H_2C=$CHCH_2Cl$	$Rh_6(CO)_{16}$	26	7:93 (1.22)
	$Rh_2(OAc)_4$	95	5:95 (1.16)

[a] Reactions were performed at 25 °C; 0.5 mol % of catalyst was employed. [b] Isolated product yield. [c] Ratio of cyclopropane geometrical isomers ±0.03.

between the allyl substrate and ethyl diazoacetate on rhodium.

Allyl Halonium Ylides. The photochemically induced reactions of dimethyl diazomalonate and ethyl diazoacetate with allyl bromide and a variety of allyl chlorides have been investigated by Ando and co-workers in considerable detail.[17,37] Products from cyclopropanation are formed in competition with those from ylide generation, although ylide formation is usually the preferred process in reactions with the singlet carbene.[37] In contrast, metal-catalyzed reactions of diazo compounds with ally halides have received scant attention despite the potential singular advantage of the catalytic approach for exclusive ylide generation and subsequent [2,3] sigmatropic rearrangement. Copper catalysts, which have been the only ones investigated thus far, have been employed for the decomposition of dimethyl diazomalonate[17a] and ethyl diazoacetate[17b] in the presence of several allyl chlorides. However, relatively high temperatures were employed for these reactions, low yields of cyclopropane and ylide rearrangement products were obtained, and product mixtures were complex.

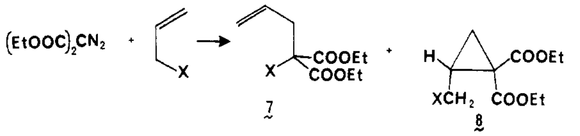
In view of the pronounced activity of rhodium catalysts for cyclopropanation[33,34] and ylide generation, we anticipated that these catalysts could be advantageously employed for the production of halonium ylides. Furthermore, we expected that competition between ylide generation and cyclopropanation could be manipulated by varying the nucleophilicity of halogen[38,39] in the reactant allyl halide. Results from rhodium-catalyzed reactions of ethyl diazoacetate with allyl halides are presented in Table II and describe a spectrum of activities that entail competition between ylide rearrangement and cyclopropanation (eq 3). Reactions with allyl iodide result solely in the product expected from [2,3] sigmatropic rearrangement of an intermediate ylide, whereas cyclopropanation occurs almost exclusively with allyl chloride. Competition between these two transformations is exhibited in reactions with allyl bromide, and identical product ratios (5/6) are observed with the two active rhodium catalysts. The exceptional activity of rhodium catalysts for ylide transformations with allyl iodide is exemplified by the observed 59% and 72% recovery of 5 from $Rh_2(OAc)_4$-catalyzed reactions in which the allyl iodide to ethyl diazoacetate molar ratios were only 1.2 and 2.0, respectively. Comparison of these results to those for allyl methyl sulfide demonstrates that iodides and sulfides are very similar in their ability to intercept carbenoid intermediates.



(3)

In contrast to the results described in Table I, the hexadecacarbonylhexarhodium catalyst is not as effective as the rhodium(II) acetate dimer for transformations involving allyl halides. Although the cause for this reversal in catalytic effectiveness cannot be known with certainty, the susceptibility of the rhodium carbonyl cluster to substitution reactions by weak bases[36] may be a factor.[40] With either catalyst, however, diethyl maleate, diethyl fumarate, and a high molecular weight substance derived solely from the diazo ester are formed in the only competing processes. For example, in addition to the cyclopropane products formed in the rhodium(II) acetate catalyzed reaction of ethyl diazoacetate with allyl chloride (Table I), diethyl maleate and diethyl fumarate are also produced (18% yield), and the remainder of the reactant ethyl diazoacetate is incorporated in the high molecular weight substance. The relative proportions of these byproducts are variable, but diethyl maleate and fumarate are observed to increase in importance as the yields of 5 and/or 6 approach their maximum, which suggests that the polymeric substance is derived from these esters.

Diethyl diazomalonate reacts with allyl bromide at 60 °C to produce ylide derived 7 as the predominant product (eq 4; for $Rh_2(OAc)_4$; 92% yield, 7/8 ratio of 93:7; for $Rh_6(CO)_{16}$; 82% yield, 7/8 ratio of 88:12). Compared to results obtained for ethyl diazoacetate, reactions of diazomalonate with allyl bromide produce a dramatic reversal in the relative reactivities of the carbenoid species toward the nucleophilic bromide and the carbon–carbon double bond. Similar reversals in heteroatom/olefin relative reactivities are evident when comparison is made of copper-catalyzed reactions of dimethyl diazomalonate,[17a] ethyl diazoacetate,[17b] and diazomethane[41] with allyl methyl ethers. These results are in accord with a greater electrophilic selectivity of the dicarboalkoxy carbenoid intermediate relative to the carboethoxy carbenoid.[42] That increasing the electrophilicity of the carbenoid intermediate can reverse its reactivity toward the nucleophilic heteroatom relative to the olefin is consistent with the nature of nucleophilic reactions.[43] Indeed, the ratios of products formed by competitive ylide generation and cyclopropanation with the allyl halides appear to provide a convenient measure for the relative electrophilicities of carbenoid systems, and efforts are underway to examine this measure in detail.



(4)

With allyl chloride, the $Rh_2(OAc)_4$-catalyzed reaction at 60 °C produces 8 predominantly (eq 4; 82% yield, 7/8 ratio of 8:92). Curiously, nearly identical results were obtained from reactions with ethyl diazoacetate (Table II), although

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Table III. Temperature Dependence on Product Yields from Copper- and Rhodium-Catalyzed Reactions of Ethyl Diazoacetate with Allyl Bromide and Allyl Chloride[a]

allyl halide	catalyst	temp, °C	% yield[b] of 5 + 6	5/6 ratio[c]	*trans*-6/*cis*-6 ratio[c]
$H_2C{=}CHCH_2Br$	$Rh_2(OAc)_4$	60	67	0.23	1.2
		25	76	0.40	1.1
		4	72	0.34	1.2
	$CuCl{\cdot}P(O\text{-}i\text{-}Pr)_3$	60	77	13	2.0
		25	49	5.8	1.8
	copper bronze	60	64	13	2.0
		25	56	7.8	1.8
$H_2C{=}CHCH_2Cl$	$Rh_2(OAc)_4$	45	75	0.055	1.2
		25	95	0.053	1.2
	$CuCl{\cdot}P(O\text{-}i\text{-}Pr)_3$	45	90	0.88	2.1
		25	86	0.73	1.8
	copper bronze[d]	45	19	0.21	1.9
		25	23	0.22	1.9

[a] Except in reactions catalyzed by Cu, 0.5-1.0 mol % of catalyst, based on ethyl diazoacetate, was employed. Copper bronze (15 mol %) was used. [b] Isolated product yield. [c] Values are reproducible to within ±3% of the reported values. [d] No yield improvement was observed at twice the reaction times employed to obtain these results.

Table IV. Product Yields from Copper- and Rhodium-Catalyzed Reactions of Ethyl Diazoacetate with Crotyl Bromide at Representative Temperatures[a]

		rel yield, %					
catalyst	temp, °C	9	10	11[b]	$BrCH_2COOEt$[c]	Σyield,[d] %	% ECH=CHE
$Rh_2(OAc)_4$	4	76	0	24	<1	82	<1
	25	67	0	33	<1	77	<2
	40	35	16	22	27	47	5
	50	17	13	16	54	26	8
$Cu(acac)_2$	25	43	45	7	5	61	5
	50	40	47	5	8	31	4
$CuCl{\cdot}P(O\text{-}i\text{-}Pr)_3$	4	46	34	4	16	34	<2
	25	32	53	6	9	68	4
	50	39	39	6	16	13	8
copper bronze	25	34	52	7	7	67	3
	50	28	29	4	39	50	<2

[a] Except in reactions catalyzed by Cu, 1.0 mol % of catalyst, based on ethyl diazoacetate, was employed. Copper bronze (15 mol %) was used. [b] Estimated for copper-catalyzed reactions with the assumption that the major isomer, whose yield could be accurately determined, was formed in a 2-fold excess over the minor isomer, whose yield could not be accurately determined. [c] Observed in variable yields from reactions performed above 25 °C. Reported yields have been averaged from at least duplicate experiments and are accurate to within ±5% of the reported yields. [d] Isolated yields of 9 + 10 + 11 + $BrCH_2COOEt$.

at a lower temperature. Clearly, allyl chloride is not as responsive to changes in the electrophilicity of the generated carbene intermediate as is allyl bromide, but the cause of this leveling effect remains speculative.

Rhodium vs. Copper Catalysis. The results that are reported here for the rhodium-catalyzed reactions of diazomalonate and diazoacetate with allyl chloride and allyl bromide differ markedly from those obtained with copper catalysts. Whereas in the rhodium-catalyzed reactions there is clear differentiation between allyl chloride and bromide in their reactions with diazo compounds, in the copper-catalyzed reactions the ylide product is reported to dominate even when allyl chloride is the reactant.[17b,44] More significantly, however, copper-catalyzed reactions of ethyl diazoacetate with allyl halides yield products derived from both the [2,3] and the [1,2] sigmatropic rearrangements.[17b,44] Since the copper-catalyzed reactions were previously performed at relatively high temperatures, low product yields were obtained, and comparable data that would equate rhodium and copper catalysts in reactions with allyl bromide and allyl chloride have not been reported, we have reinvestigated the copper-catalyzed reactions under conditions comparable to those employed for the rhodium-catalyzed transformations.

Results from copper- and rhodium-catalyzed reactions of ethyl diazoacetate with allyl bromide and allyl chloride are presented in Table III. The triisopropylphosphite complex of copper(I) chloride[45] was chosen for comparison because of its solubility in the reaction media and its derivative similarity to the previously employed copper(I) chloride. Copper bronze was chosen to represent a heterogeneous catalyst counterpart to the soluble copper catalyst. The reaction temperature was varied in order to assess the effect of this reaction variable on the ratio of the ylide rearrangement product (**5**) to cyclopropane products (**6**).

Rhodium and copper catalysts are clearly dissimilar in their effect. Rhodium(II) acetate catalysis results in the production of significantly less of the ylide rearrangement product than either $CuCl{\cdot}P(O\text{-}i\text{-}Pr)_3$ or Cu. Furthermore, the product ratio **5**/**6** is relatively independent of temperature in $Rh_2(OAc)_4$-catalyzed reactions, whereas a significant temperature dependence on the **5**/**6** product ratio is observed in the copper-catalyzed reactions. The nearly identical behavior of $CuCl{\cdot}P(O\text{-}i\text{-}Pr)_3$ and Cu in allyl bromide reactions with ethyl diazoacetate suggests that the active copper catalysts in these reactions are very similar[46] and clearly points to an all but minor role of the

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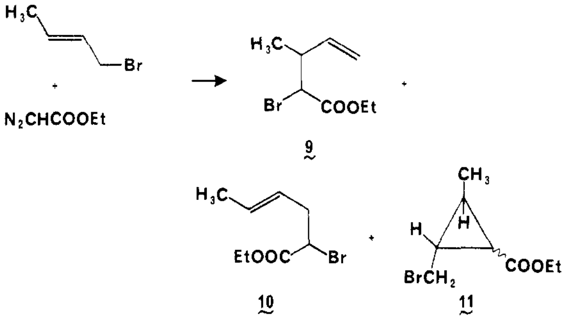
(44) Philips, D. D. *J. Am. Chem. Soc.* **1954**, *76*, 5385.

(45) Moser, W. R. *J. Am. Chem. Soc.* **1969**, *91*, 1135.

trialkylphosphite ligand in product determination. Results with allyl chloride are less obvious with regard to copper catalyst similarity, but copper bronze is only a marginally effective catalyst with this reactant.

In order to assess the relative importance of the [2,3] and [1,2] sigmatropic rearrangements, we have examined the copper- and rhodium-catalyzed reactions of ethyl diazoacetate with crotyl bromide (eq 5) under reaction conditions that do not isomerize this reactive halide. The results of this study are presented in Table IV. Only the [2,3] sigmatropic rearrangement product **9** is observed from the $Rh_2(OAc)_4$-catalyzed reactions performed at or below 25 °C, whereas both **9** and **10** are produced in the copper-catalyzed transformations under these same conditions. In addition to the products derived from crotyl bromide, ethyl bromoacetate is also produced in the copper-catalyzed reactions. With $Rh_2(OAc)_4$ at 50 °C, both **9** and **10** are produced, and ethyl bromoacetate, which is absent in reaction mixtures obtained at or below room temperature, is now observed.



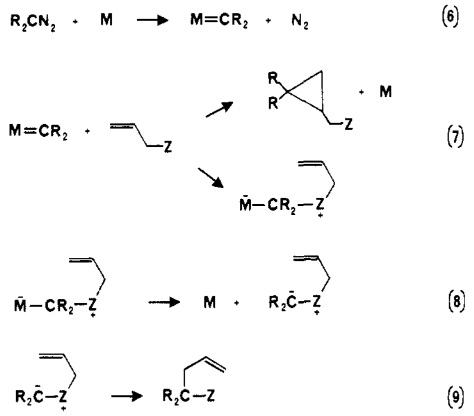
(5)

Not previously observed in corresponding reactions performed with allyl bromide (Table III) was the decrease of the ratio of ylide-derived products to cyclopropane products (**9**/**11**) with temperature for $Rh_2(OAc)_4$-catalyzed reactions performed at or below 25 °C. In the corresponding copper-catalyzed reactions, accurate yields for **11** could not be determined because of their minor role in product formation (<3%) and because of the presence of several byproducts that masked their analysis; estimated values (±2% in relative yield) are reported.

Reactions performed at 50 °C generally gave poor accountability for products derived from ethyl diazoacetate and crotyl bromide. However, although total product yields were observed to vary widely in reactions performed at this temperature and an array of new products could be detected, consistent product ratios for **10**/**9** were obtained in multiple individual experiments with each of the catalysts that were employed.

Isomerization of crotyl bromide to an equilibrium mixture consisting of 82% crotyl bromide and 18% of 3-bromo-1-butene occurred during the course of reactions performed at 40 and 50 °C. The presence of either copper or rhodium catalysts did not affect the isomer distribution in the equilibrium mixture. Since 3-bromo-1-butene is capable of forming **10** by [2,3] sigmatropic rearrangement of a corresponding intermediate ylide, its reactivity relative to that of crotyl bromide was determined. Treatment of a mixture consisting of 62% crotyl bromide and 38% 3-bromo-1-butene with ethyl diazoacetate at 25 °C and employing $Rh_2(OAc)_4$ as the catalyst gave ylide-derived and cyclopropane products in 66% yield. The relative yields of the individual products were as follows: **9**, 45%; **10**, 20%; cyclopropane products, 35%. Thus crotyl bromide is 1.4 times more reactive than 3-bromo-1-butene in ylide-derived transformations, and even with the equilibrium mixture of isomeric bromides ([crotyl bromide]/[3-bromo-1-butene] = 4.5), crotyl bromide is the preferred reactant by a factor of 6.3. Consequently, the maximum amount of ylide-derived products resulting from reactions with 3-bromo-1-butene at 50 °C is 14% of the total amount of **9** and **10**.

Scheme II



Discussion

That the [2,3] sigmatropic rearrangement would be the sole process operative in the $Rh_2(OAc)_4$-catalyzed reactions was not anticipated. Photochemical generation of carbethoxycarbene from ethyl diazoacetate in the presence of crotyl chloride had been shown to result in the production of the ylide mixture corresponding to **9** plus **10**.[17b] However, low product yields were obtained in the photochemical process with crotyl chloride, and it is conceivable that reactant or product isomerization occurred during the photochemical process or that the photochemically generated carbene possessed sufficient excess energy that ground-state behavior was not exhibited.

Ollis and co-workers have recently examined reported observations of Stevens [1,2] rearrangements that appear to occur in competition with the [2,3] sigmatropic rearrangement, and they have concluded that the symmetry-allowed [2,3] sigmatropic rearrangement is the favored pathway in base-promoted rearrangements of allylammonium and sulfonium ylides.[8b] They explain the [1,2] rearrangement, when such a process is not accounted for by a combination of symmetry-allowed transformations, as arising through a dissociation–recombination process involving a radical pair derived from the corresponding ylide, and their explanation is consistent with proposals that the concerted [1,2] rearrangement is a forbidden process.[47-49] Ando has suggested a similar explanation to account for competitive [1,2] and [2,3] rearrangements in the photochemically induced reactions of ethyl diazoacetate with allyl ethers and chlorides.[17b] Thus the sole occurrence of the symmetry-allowed [2,3] sigmatropic rearrangement, as is observed in the rhodium-catalyzed reactions of ethyl diazoacetate with allylic substrates, is the singular transformation expected from simple allyl ylides, and observations of competitive [2,3] and [1,2] rearrangements in the photochemical and copper-catalyzed processes deviate from their expected behavior.

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(46) Copper bronze is observably oxidized by allyl bromide under these conditions.

(47) Ollis, W. D.; Sutherland, I. O.; Thebtaranonth, Y. *J. Chem. Soc., Chem. Commun.* **1973**, 653, 654.

(48) Baldwin, J. E.; Andrist, A. H.; Pinschmidt, R. K., Jr. *Acc. Chem. Res.* **1972**, *5*, 402.

(49) (a) Berson, J. A. *Acc. Chem. Res.* **1972**, *5*, 406. (b) Berson, J. A.; Holder, R. W. *J. Am. Chem. Soc.* **1973**, *95*, 2037.

Table V. Product Ratios from Copper- and Rhodium-Catalyzed Reactions of Ethyl Diazoacetate with Crotyl Bromide at Representative Temperatures[a]

catalyst	temp, °C	diastereomer ratio for 9[b]	10/9 ratio[c]	(9 + 10)/11 ratio[d]	*trans*-11/ *cis*-11 ratio[e]
$Rh_2(OAc)_4$	4	1.20	0	3.10	2.0
	25	1.18	0	2.01	2.2
	40	0.90	0.44	2.3	1.9
	50	0.80	0.73	1.8	2.1
$Cu(acac)_2$	25	0.92	1.04	13	
	50	0.80	1.18	17	
$CuCl \cdot P(O\text{-}i\text{-}Pr)_3$	4	0.86	0.74	20	
	25	0.89	1.66	14	
	50	0.77	1.00	13	
copper bronze	25	0.77	1.52	12	
	50	0.81	0.97	14	

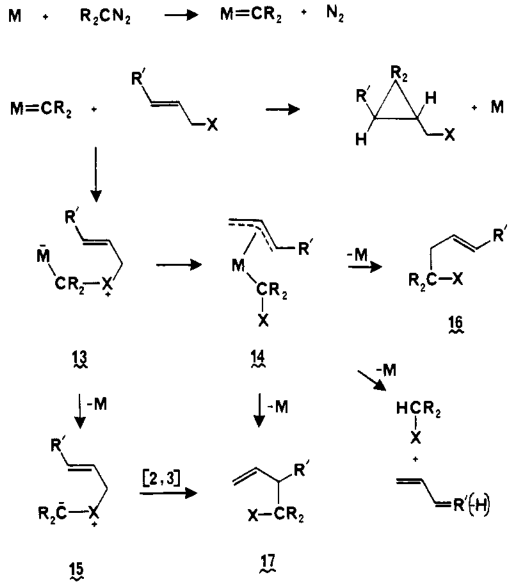
[a] Data calculated from the yields reported in Table IV. [b] Values are reproducible to within ±0.03 of the reported values. [c] Corrected for the presence of 3-bromo-1-butene in reactions performed at or below 25 °C. Values are reproducible to within ±5% of the reported values. [d] Estimated values for copper-catalyzed reactions. [e] The cis and trans notation refers to the geometrical relationship between the carboethoxy group and the bromomethyl group of the cyclopropane isomers. The trans relationship between methyl and bromomethyl in the reactant crotyl bromide remains intact in the product.

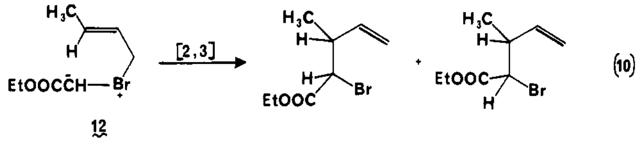
The results obtained for the rhodium-catalyzed reactions of diazo compounds with allylic substrates are in accord with the mechanistic pathway that is depicted in Scheme II. Generation of the proposed metal carbene intermediate (eq 6) is not inhibited by allyl halides although, as evidenced by the higher temperatures required for similar transformations with allyl sulfides and amines, these nucleophilic reagents do compete with the diazo compound for available coordination sites on the catalyst. Direct competition then exists between the olefin and substrate heteroatom for reactions at the carbenic center (eq 7). That the product ratio derived from this competition is not markedly temperature dependent (Table III) suggests that these processes are subject to similar kinetic constraints. Dissociation of the metal (eq 8) unmasks the allyl ylide which readily undergoes the [2,3] sigmatropic rearrangement (eq 9).

The results obtained for copper catalysis present a less clear picture of the mechanistic events that occur in reactions of diazo compounds with allylic substrates. With allyl sulfides only products derived from the [2,3] sigmatropic rearrangement are obtained whether methyl diazomalonate[17a,50] or ethyl diazoacetate[17b,18,51] is employed,[52] and these results are consistent with the mechanistic description in Scheme II. However, crotyl chloride[17b,44] and crotyl bromide (Table IV) both react with ethyl diazoacetate in copper-catalyzed reactions to produce products derived from the [2,3] and [1,2] rearrangement processes, and parallel behavior is exhibited by $Rh_2(OAc)_4$ for reactions of ethyl diazoacetate with crotyl bromide at reaction temperatures above 25 °C. The mechanistic relationship between the [2,3] and [1,2] rearrangement processes for reactions in which both products are formed is suggested by the variations in the diastereomeric product ratio for **9** that is obtained in these transformations (Table V).

The stereoselectivity exhibited in the [2,3] sigmatropic rearrangement is independent of the catalyst employed for ylide generation, and results obtained for allylamines **5d** and **5e** (Table I) support this interpretation. Thus the stereoisomeric ylide rearrangement products **9** generated by the $Rh_2(OAc)_4$-catalyzed reaction of ethyl diazoacetate with crotyl bromide at or below 25 °C are those derived from ylide **12** (eq 10). In accord with Scheme II, the diastereomer ratio for **9** is relatively independent of temperature. If **12** is similarly produced in the copper-catalyzed reactions, the identical stereoisomer ratio should be observed. That these ratios are not identical (Table V) with those obtained for the $Rh_2(OAc)_4$-catalyzed reactions at or below room temperature demonstrates that all or part of **9** is derived from processes other than the [2,3] sigmatropic rearrangement.

Scheme III





Scheme III adequately accounts for the results obtained from the copper-catalyzed reactions of ethyl diazoacetate with crotyl bromide and with those previously obtained with crotyl chloride[17b] and the allyl halides (Table III). Cyclopropane and metal ylide (**13**) formation are again represented as competing processes for the capture of the metal carbene intermediate. However, **13** is now proposed to undergo competitive metal-induced rearrangement to the allylmetal complex **14**[53] as well as metal dissociation

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(50) Grieco, P. A.; Meyers, M.; Finkellor, R. S. *J. Org. Chem.* **1974**, *39*, 1198.

(51) Yoshimoto, M.; Ishihara, S.; Nakayama, E.; Soma, N. *Tetrahedron Lett.* **1972**, 2923.

(52) However, dichlorocarbene has been reported to react with 1-buten-3-yl phenyl sulfide to form products derived from both the [2,3] and [1,2] ylide rearrangement pathways: Parham, W. E.; Groen, S. H. *J. Org. Chem.* **1964**, *29*, 2214.

resulting in ylide **15**. Subsequent reductive elimination[55,56] of **14** leads to the competitive production of the observed [1,2] and [2,3] rearrangement products **16** and **17**, as well as of ethyl bromoacetate. Ethyl bromoacetate is not observed in either copper- or rhodium-catalyzed reactions of ethyl diazoacetate with allyl bromide, nor is ethyl chloroacetate observed in reactions with allyl chloride.

The diastereomer ratios for **9** and the **10**/**9** product ratios set apart the alternate pathways for the production of **17**. As evidenced by the absence of **10** and of ethyl bromoacetate, only the dissociative pathway **13** → **15** is followed in the rhodium(II) acetate catalyzed reactions of ethyl diazoacetate with crotyl bromide that are performed at or below 25 °C. In these reactions the diastereomer ratio for **9** is 1.2. When the temperature is raised above 25 °C for the rhodium catalyzed transformations, the diastereomer ratio for **9** decreases to 0.8, **10** and ethyl bromoacetate are observed for the first time, and the **10**/**9** ratio is seen (Table V) to increase with increasing temperature. Thus, above 25 °C in $Rh_2(OAc)_4$-catalyzed reactions, **17** arises from both **14** and **15**.

In copper-catalyzed reactions of ethyl diazoacetate with crotyl bromide, the diastereomer ratio for **9** is less than 1.0 with each of the catalysts and at all reaction temperatures investigated in this study. In each case, **10** and ethyl bromoacetate are observed in addition to **9**. Thus the conversion of **13** to the allylcopper complex **14** appears to be the major determinant of product formation in copper-catalyzed reactions of ethyl diazoacetate with allyl halides. If the diastereomer ratio for **9** of 0.77 (Table V) is taken as the limiting value for the **14** → **17** transformation and 1.18 is the diastereomer ratio for the **15** → **17** conversion, the relative contribution to **17** from each of the reaction intermediates, **14** and **15**, can be estimated[56] (at 25 °C for **14** → **17**): $Cu(acac)_2$, 63%; $CuCl{\cdot}P(O\text{-}i\text{-}Pr)_3$, 71%; copper bronze, 100%.[57]

The composite data suggest several generalizations regarding the nature and activities of reaction intermediates in metal-catalyzed transformations of diazo compounds with allylic substrates. (1) Nucleophilic addition to catalytically generated metal carbenes is competitive with cyclopropanation and, as is indicated by the temperature dependence of the ratio of ylide-derived products to cyclopropane products (Tables III and V), may be reversible (eq 1). (2) The metal carbene derived from catalytic reactions of diazomalonate is more selective than that derived from ethyl diazoacetate. Consequently, reactions of allylic substrates with diazomalonate uniformly provide higher yields of ylide-derived products than of cyclopropane products. In addition, with diazomalonate the conversion **13** → **14** is not observably competitive with metal dissociation from the metal ylide (**13** → **15**) under ordinary reaction conditions, even in reactions performed with copper catalysts. (3) The electrophilicity of catalytically generated metal carbenes is reflected in their reactions with the nucleophilic series of allylic halides. Copper carbenes are more electrophilic than are those produced in rhodium-catalyzed reactions. Copper catalysis results in significantly higher yields of ylide-derived products, relative to cyclopropane products, than does rhodium catalysis in reactions with allyl bromides and chlorides. In addition, the substantial similarity in reaction products and product ratios from copper-catalyzed processes (Tables III and V) suggests that the active catalyst in each case exists in the same oxidation state. The nature of the reaction products derived from crotyl bromide suggests that copper(I) is the active catalyst in these reactions.[54,58] (4) Finally, the metal ylide intermediate **13**, generated by nucleophilic addition of allyl halides to metal carbenes, is subject to metal-induced rearrangement that is competitive with metal dissociation (**13** → **15**). The absence of such a rearrangement transformation with ammonium (Table I) and sulfonium[17b] ylides analogous to **13** suggests that this process is dependent on the leaving group ability of the allyl substituent ($M^-CR_2\text{-}X^+$) in **13**. In addition, the relative rate for the **13** → **14** rearrangement process is similarly dependent on the nature of the metal and of the carbene substituents. The details of this transformation and its implications for catalytic coupling processes are currently under investigation.

Experimental Section

General Methods. Proton magnetic resonance spectra were obtained with the Varian FT-80A spectrometer; chemical shifts are reported in δ units with tetramethylsilane as the internal standard. Analytical gas chromatographic analyses were performed on a Varian Aerograph Model 2720 gas chromatograph with thermal-conductivity detectors. Elemental analyses were performed by Galbraith Laboratories, Inc., on product samples that were isolated and purified by gas chromatography. Rhodium(II) acetate was obtained from Alfa, and hexadecacarbonylhexarhodium was purchased from both Alfa and Strem Chemicals. The purity of the hexarhodium carbonyl cluster was determined quantitatively by infrared analysis of the carbonyl stretching frequencies relative to an internal standard, adamantanone, on a Perkin-Elmer Model 621 grating spectrophotometer. Copper(I) chloride triisopropylphosphite[45] and copper bronze[59] were prepared by standard procedures. Solvents were rigorously dried and then distilled prior to their use. *N*,*N*-Dimethyl-3,3-dimethylallylamine (**4c**)[8a,60] and *N*,*N*-dimethylcinnamylamine **(4e)8b** were prepared by previously reported methods. (*trans*-2-Buten-1-yl)dimethylamine (**4d**)[61] was prepared from commercially available crotyl bromide by the same procedure as that used in the preparation of **4e**.[8b] Diethyl diazomalonate was prepared from diethyl malonate and tosyl azide.[62]

Reactions of Ethyl Diazoacetate with Allyl Sulfides and Amines. Ethyl diazoacetate (2.0 mmol) in benzene, cyclohexane, or the allyl substrate (2.0 mL) was added over a 24–30-h period (Sage Model 355 syringe pump) to a stirred mixture, heated at 60 °C, of the catalyst (0.5–1.0 mol % based on ethyl diazoacetate) and the allyl substrate (usually 5- to 10-fold molar excess). Although not generally required, reactions were performed under an inert atmosphere of nitrogen or argon. Rhodium(II) acetate readily dissolves in these reaction media to produce a pink solution; the rhodium carbonyl cluster is only partially soluble. Following complete addition, the reaction mixture was diluted with ether, the resulting solution was extracted with saturated sodium bicarbonate, and products were isolated by standard procedures. Isolated yields were determined by GC analyses using an internal standard (benzyl ether) and calculated with the use

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(53) Although a π-allyl complex (**14**) is the most efficient formalism for these processes, such an intermediate cannot be distinguished here from the composite set of σ-allylcopper complexes.

(54) Kochi, J. K. "Organometallic Mechanisms and Catalysis"; Academic Press: New York, 1978; Chapter 15, pp 381–386.

(55) Cohen, T.; Tirpak, J. G. *Tetrahedron Lett.* 1975, 143.

(56) Such an estimate assumes that the diastereomer ratio for **9** obtained from the transformation **14** → **17** is independent of the metal and its attendant ligands. Thus only the minimum contribution for **14** → **17** can be determined.

(57) Evaluation of the extent of the conversion of **13** → **14** relative to **13** → **15** and consequent determination of selectivity in **14** → **16** and **14** → **17** conversions is also possible. However, product accountability permits only a qualitative estimate that **14** favors **16** relative to **17** in copper-catalyzed reactions of ethyl diazoacetate with crotyl bromide.

(58) Salomon, R. G.; Kochi, J. K. *J. Am. Chem. Soc.* **1973**, *95*, 3300.

(59) Fuson, R. C.; Cleveland, E. A. "Organic Syntheses"; Wiley: New York, 1955; Collect. Vol. III, p 339.

(60) Martirosyan, G. T.; Grigoryan, E. A.; Babayan, A. T. *Izv. Akad. Nauk, Arm. SSR, Khim. Nauki* **1965**, *18*, 161; *Chem. Abstr.* **1965**, *63*, 14686.

(61) Larcheveque, M.; Giullaumet, G.; Cuvigny, T.; Caubere, P. *Bull. Soc. Chim. Fr.* **1975**, 2275.

(62) Regitz, M. *Synthesis* **1972**, 351.

of previously determined thermal-conductivity values. The average results from duplicate or triplicate experiments are reported in Table I. Diastereoisomeric separations were conveniently obtained by GC analyses on a 2-m Carbowax 20M column. The absence of cyclopropane products (<0.2%) was evaluated by GC and NMR analyses. Reaction products were stable to the reaction conditions and to the conditions employed for GC analyses.

Ethyl 2-(thiomethyl)-4-pentenoate (5a): ^{1}H NMR (DCDl$_3$) δ 6.07–5.57 (m, 1 H), 5.27–5.00 (m, 2 H), 4.20 (q, *J* = 7.1 Hz, CH$_2$O), 3.24 (dd, *J* = 7.2, 8.0 Hz, CH–S), 2.85–2.20 (m, 2 H), 2.15 (s, SMe), 1.28 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Anal. Calcd for $C_8H_{14}O_2S$: C, 55.15; H, 8.12; S, 18.40. Found: C, 55.34; H, 8.20; S, 18.28.

Ethyl 2-(dimethylamino)-4-pentenoate (5b): ^{1}H NMR (CDCl$_3$) δ 6.06–5.55 (m, 1 H), 5.23–4.96 (m, 2 H), 4.18 (q, *J* = 7.1 Hz, CH$_2$O), 3.19 (t, *J* = 7.4 Hz, CH–N), 2.55–2.33 (m, 2 H), 2.35 (s, NMe$_2$), 1.28 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Anal. Calcd for $C_9H_{17}NO_2$: C, 63.11; H, 10.02. Found: C, 62.93; H, 9.84.

Ethyl 2-(dimethylamino)-3,3-dimethyl-4-pentenoate (5c): ^{1}H NMR (CDCl$_3$) δ 6.12 (dd, J_{cis} = 10.5 Hz, J_{trans} = 17.8 Hz, 1 H), 5.01 (d of d, J_{trans} = 17.8 Hz, J_{gem} = 1.6 Hz, 1 H), 4.97 (dd, J_{cis} = 10.5 Hz, J_{gem} = 1.6 Hz, 1 H), 4.18 (q, *J* = 7.1 Hz, CH$_2$O), 2.96 (s, CH–N), 2.36 (s, NMe$_2$), 1.29 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 1.15 (s, CH$_3$), 1.10 (s, CH$_3$).

Anal. Calcd for $C_{11}H_{21}NO_2$: C, 66.28; H, 10.64; N, 7.03. Found: C, 66.56; H, 10.71; N, 6.97.

Ethyl 2-(Dimethylamino)-3-methyl-4-pentenoate. Compound **5d** (major isomer): ^{1}H NMR (CDCl$_3$; ABMXY system) δ 2.96 (H$_A$), 2.9–2.4 (H$_B$), 5.82 (H$_M$), 5.09 (H$_X$, trans to H$_M$), 5.06 (H$_Y$, cis to H$_M$) [$\mathrm{CH_ACH_BCH_M{=}CH_XH_Y}$, J_{AB} = 10.5, J_{BM} = 7.6, J_{MX} = 17.3, J_{MY} = 9.6, J_{XY} = 2.0, J_{BX} = 0.6, J_{BY} = 0.4 Hz], 4.20 (q, *J* = 7.1 Hz, CH$_2$O), 2.32 (s, NMe$_2$), 1.29 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 0.97 (d, *J* = 6.4 Hz, C$\mathbf{H}_3$CH$_B$). Compound **5d** (minor isomer): ^{1}H NMR (CDCl$_3$, ABMXY system) δ 2.92 (H$_A$), 2.9–2.4 (H$_B$), 5.70 (H$_M$), 5.05 (H$_X$, trans to H$_M$), 4.97 (H$_Y$, cis to H$_M$) [$\mathrm{CH_ACH_BCH_M{=}CH_XH_Y}$, J_{AB} = 10.3, J_{BM} = 7.4, J_{MX} = 17.2, J_{MY} = 9.8, J_{XY} = 2.0, J_{BX} = 0.6, J_{BY} = 0.3 Hz], 4.04 (q, *J* = 7.1 Hz, CH$_2$O), 2.32 (s, NMe$_2$), 1.25 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 1.06 (d, *J* = 6.4 Hz, C$\mathbf{H}_3$CH$_B$).

Anal. Calcd for $C_{10}H_{19}NO_2$: C, 64.81; H, 10.36; N, 7.56. Found: C, 64.76; H, 10.50; N, 7.30.

Ethyl 2-(Dimethylamino)-3-phenyl-4-pentenoate. Compound **5e** (major isomer): ^{1}H NMR (CDCl$_3$) δ 7.3–7.1 (m, 5 H), ABMXY system, 3.53 (H$_A$), 3.77 (H$_B$), 6.14 (H$_M$), 5.07 (H$_X$, trans to H$_M$), 5.10 (H$_Y$, cis to H$_M$) [$\mathrm{CH_ACH_BCH_M{=}CH_XH_Y}$, J_{AB} = 11.7, J_{BM} = 7.3, J_{MX} = 18.2, J_{MY} = 8.6, J_{XY} = 1.7, J_{BX} = 0.8, J_{BY} = 0.6, J_{AM} = 0.6 Hz], 3.88 (q, *J* = 7.1 Hz, CH$_2$O), 2.41 (s, NMe$_2$), 0.94 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O). Compound **5e** (minor isomer): ^{1}H NMR (CDCl$_3$) δ 7.4–7.1 (m, 5 H), ABMXY system, 3.54 (H$_A$), 3.78 (H$_B$), 5.88 (H$_M$), 5.05 (H$_X$, trans to H$_M$), 5.00 (H$_Y$, cis to H$_M$) [$\mathrm{CH_ACH_BCH_M{=}CH_XH_Y}$, J_{AB} = 11.2, J_{BM} = 7.3, J_{MX} = 17.1, J_{MY} = 9.8, J_{XY} = 1.7, J_{BX} = 0.8, J_{BY} < 0.2 Hz], 4.18 (q, *J* = 7.1 Hz, CH$_2$O), 2.25 (s, NMe$_2$), 1.27 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Anal. Calcd for $C_{15}H_{21}NO_2$: C, 72.83; H, 8.57. Found: C, 72.81; H, 8.49.

Reactions of Ethyl Diazoacetate with Allyl Halides. Ethyl diazoacetate (2.0 mmol) in cyclohexane (5.0 mL) or the allyl substrate (2.0 mL) was added over an 18–72-h period to a stirred mixture, maintained at the specified temperature, of the catalyst and the allyl halide (usually 5- to 10-fold molar excess). Reactions performed with rhodium catalysts required less than 24 h for addition, even when performed at 4 °C, for each of the allyl halides. An addition time of 72 h was employed for reactions of ethyl diazoacetate with allyl chloride when copper catalysts were used at 25 °C. The copper catalysts were not effective in inducing reactions of ethyl diazoacetate with allyl bromide at 4 °C. Reactions were performed under an inert atmosphere. Following complete addition, the reaction mixture was diluted with ether, the resulting solution was extracted with 10% aqueous hydrochloric acid, and products were isolated by standard procedures. Isolated yields were determined by GC analyses using an internal standard (benzyl ether) and calculated with the use of previously determined thermal-conductivity values. The averaged results from duplicate or triplicate experiments are reported in Tables II and III. Cyclopropane geometrical isomers were separated by GC analyses on either a 2-m Carbowax 20M column or a 4-m ethylene glycol adipate column. The absence of cyclopropane products in reactions with allyl iodide (<0.2%) was evaluated by GC and NMR analyses. Reaction products were stable to the reaction conditions and to the conditions employed for GC analyses.

Ethyl 2-iodo-4-pentenoate:[44] ^{1}H NMR (CDCl$_3$) δ 6.06–5.49 (m, 1 H), 5.29–5.00 (m, 2 H), 4.30 (t, *J* = 7.6 Hz, CHI), 4.20 (q, *J* = 7.1 Hz, CH$_2$O), 2.89–2.65 (m, 2 H), 1.27 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Ethyl 2-bromo-4-pentenoate:[44] ^{1}H NMR (CDCl$_3$) δ 6.03–5.53 (m, 1 H), 5.30–5.02 (m, 2 H), 4.22 (t, *J* = 7.4 Hz, CHBr), 4.24 (q, *J* = 7.1 Hz, CH$_2$O), 3.09–2.50 (m, 2 H), 1.29 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Ethyl *cis*-2-(bromomethyl)cyclopropanecarboxylate:[44] ^{1}H NMR (CDCl$_3$) 4.18 (q, *J* = 7.1 Hz, CH$_2$O), 3.88–3.44 (m, CH$_2$Br), 2.01–1.58 (m, 2 H), 1.39–1.11 (m, 2 H), 1.29 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Ethyl *trans*-2-(bromomethyl)cyclopropanecarboxylate:[44] ^{1}H NMR (CDCl$_3$) 4.06 (q, *J* = 7.1 Hz, CH$_2$O), 3.26 (d, *J* = 7.0 Hz, CH$_2$Br), 1.97–1.13 (m, 3 H), 1.19 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 0.98–0.75 (ddd, *J* = 8.4, 5.8, 4.3 Hz, 1 H).

Ethyl 2-chloro-4-pentenoate:[17b] ^{1}H NMR (CDCl$_3$) δ 6.06–5.56 (m, 1 H), 5.31–5.03 (m, 2 H), 4.28 (t, *J* = 7.1 Hz, CHCl) 4.24 (q, *J* = 7.1 Hz, CH$_2$O), 2.83–2.60 (m, 2 H), 1.30 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Ethyl *cis*-2-(chloromethyl)cyclopropanecarboxylate:[17b] ^{1}H NMR (CDCl$_3$) δ 4.18 (q, *J* = 7.1 Hz, CH$_2$O), 4.01–3.55 (m, CH$_2$Cl), 2.05–1.55 (m, 2 H), 1.34–1.07 (m, 2 H), 1.28 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Ethyl *trans*-2-(chloromethyl)cyclopropanecarboxylate:[17b] ^{1}H NMR (CDCl$_3$) δ 4.14 (q, *J* = 7.1 Hz, CH$_2$O), 3.48 (d, *J* = 6.7 Hz, CH$_2$Cl), 2.05–1.54 (m, 2 H), 1.42–1.20 (m, 1 H), 1.26 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 1.07–0.83 (ddd, *J* = 8.7, 6.0, 4.5 Hz, 1 H).

Reactions of Diethyl Diazomalonate with Allyl Halides. A stirred mixture of the catalyst (0.5 mol %) and diethyl diazomalonate (2.0 mmol) in 4.0 mL of the allyl halide was heated at 60 °C under argon until gas evolution had ceased. Alternatively, the diazomalonate (2.0 mmol) in 5 mL of cyclohexane was added over a 24-h period to a stirred mixture, maintained at 60 °C, of the rhodium catalyst (0.5 mol %) and the allyl halide (usually 5- to 10-fold molar excess). Products were isolated as previously described for reactions performed with ethyl diazoacetate. Product yields and the relative amounts of 7 were greater by using the former procedure. With the latter procedure, with only a 5-fold excess of allyl bromide, product yields were 61% and 53% for reactions performed with $Rh_2(OAc)_4$ and $Rh_6(CO)_{16}$, respectively, and diethyl cyclohexylmalonate was produced as the major product when these same reactions were performed with allyl chloride in cyclohexane. No reaction was observed between allyl bromide and the diazomalonate in refluxing dichloromethane after 16 h with the hexarhodium carbonyl cluster catalyst, and only a 25% conversion to 7 and 8 was observed in the rhodium(II) acetate catalyzed reaction in refluxing dichloromethane. The products were stable to the reaction conditions and were analyzed as previously described.

Diethyl α-allyl-α-bromomalonate (7): ^{1}H NMR (CDCl$_3$) δ 6.09–5.59 (m, 1 H), 5.32–5.04 (m, 2 H), 4.28 (q, *J* = 7.1 Hz, CH$_2$O), 3.04 (ddd, *J* = 6.8, 1.1, 0.8 Hz, 2 H), 1.29 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Anal. Calcd for $C_{10}H_{15}BrO_4$: C, 43.02; H, 5.43. Found: C, 43.20; H, 5.49.

Diethyl 2-(bromomethyl)-1,1-cyclopropanedicarboxylate (8):[17a] ^{1}H NMR (CDCl$_3$) δ 4.39–4.05 (m, *cis*-CH$_2$O), 4.26 (q, *J* = 7.1 Hz, *trans*-CH$_2$O), 3.61–3.19 (m, CH$_2$Br), 2.62–2.22 (m, C$\mathbf{H}$CH$_2$Br), 1.61–1.50 (m, 2 H), 1.31 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 1.27 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Diethyl 2-(chloromethyl)-1,1-cyclopropanedicarboxylate (8): ^{1}H NMR (CDCl$_3$) 4.40–4.08 (m, *cis*-CH$_2$O), 4.26 (q, *J* = 7.1 Hz, *trans*-CH$_2$O), 3.57 (d, *J* = 7.6 Hz, CH$_2$Cl), 2.57–2.17 (m, C$\mathbf{H}$CH$_2$Cl), 1.60–1.49 (m, 2 H), 1.31 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O), 1.28 (t, *J* = 7.1 Hz, C$\mathbf{H}_3$CH$_2$O).

Anal. Calcd for $C_{10}H_{15}ClO_4$: C, 51.18; H, 6.45. Found: C, 51.16; H, 6.45.

Reactions of Ethyl Diazoacetate with Crotyl Bromide. Crotyl bromide was purified from the commercial mixture by distillation under reduced pressure.[63] Distilled fractions having a [crotyl bromide]/[3-bromo-1-butene] ratio greater than 15 were employed in metal-catalyzed reactions with ethyl diazoacetate. Reactions were performed as previously described for allyl halides. Direct analyses of the crotyl bromide content of product mixtures was performed following complete reaction, usually 24 h. At temperatures at or below 25 °C reactant isomerization was not observed, but at 50 °C isomerization to the equilibrium mixture of [crotyl bromide]/[3-bromo-1-butene] equal to 4.5 occurred during the course of the catalytic reaction. Product isolation and analyses were performed as previously described. GC analyses were performed by using 4-m 5% ethylene glycol adipate columns. The averaged results from duplicate and triplicate experiments are reported in Tables IV and V.

Ethyl 2-bromo-3-methyl-4-pentenoate (9): ^1H NMR ($CDCl_3$) of major isomer from $Rh_2(OAc)_4$-catalyzed reactions at or below 25 °C δ 5.72 (ddd, J_{trans} = 17.0 Hz, J_{cis} = 9.7 Hz, J_{vic} = 7.5 Hz, CH=), 5.11 (dd, J_{trans} = 17.0 Hz, J_{gem} = 0.9 Hz, 1 H), 5.09 (dd, J_{cis} = 9.7 Hz, J_{gem} = 0.9 Hz, 1 H), 4.20 (q, J = 7.1 Hz, CH_2O), 4.07 (d, J = 8.6 Hz, CHBr), 3.04–2.55 (sextet m, $CHCH_3$), 1.28 (t, J = 7.1 Hz, CH_3CH_2O), 1.21 (d, J = 6.7 Hz, CH_3CH); ^1H NMR ($CDCl_3$) for minor isomer δ 5.80 (ddd, J_{trans} = 17.0 Hz, J_{cis} = 9.6 Hz, J_{vic} = 7.5 Hz, CH=), 5.14 (dd, J_{trans} = 17.0 Hz, J_{gem} = 0.9 Hz, 1 H), 5.13 (dd, J_{cis} = 9.6 Hz, J_{gem} = 0.9 Hz, 1 H), 4.24 (q, J = 7.1 Hz, CH_2O), 4.11 (d, J = 8.4 Hz, CHBr), 3.04–2.55 (sextet m, $CHCH_3$), 1.29 (t, J = 7.1 Hz, CH_3CH_2O), 1.24 (d, J = 6.8 Hz, CH_3CH).

Anal. Calcd for $C_8H_{13}BrO_2$: C, 43.45; H, 5.94. Found: C, 43.62; H, 6.11.

Ethyl *trans*-2-bromo-4-hexenoate (10): ^1H NMR ($CDCl_3$) δ 5.84–5.14 (m, 2 H), 4.22 (q, J = 7.1 Hz, CH_2O), 4.16 (t, J = 7.4 Hz, CHBr), 3.00–2.40 (m, 2 H), 1.65 (ddt, J = 5.8, 2.2, 1.2 Hz, CH_3CH=), 1.29 (t, J = 7.1 Hz, CH_3CH_2O).

Anal. Calcd for $C_8H_{13}BrO_2$: C, 43.45; H, 5.94. Found: C, 43.58; H, 6.17.

Ethyl 2-(bromomethyl)-3-methylcyclopropanecarboxylate (*trans*-11): ^1H NMR ($CDCl_3$) δ 4.16 (q, J = 7.1 Hz, CH_2O), 3.91–3.43 (m, CH_2Br), 1.86–1.23 (m, 3 H), 1.28 (t, J = 7.1 Hz, CH_3CH_2O), 1.14 (d, J = 5.0 Hz, CH_3CH).

Anal. Calcd for $C_8H_{13}BrO_2$: C, 43.45; H, 5.94; Br, 36.14. Found: C, 43.63; H, 6.01; Br, 36.32.

Ethyl 2-(bromomethyl)-3-methylcyclopropanecarboxylate (*cis*-11): ^1H NMR ($CDCl_3$) δ 4.15 (q, J = 7.1 Hz, CH_2O), 3.35 (d, J = 7.2 Hz, CH_2Br), 1.95–1.60 (m, 2 H), 1.50–1.28 (m, 1 H), 1.26 (t, J = 7.1 Hz, CH_3CH_2O), 1.23 (m, CH_3CH).

Ethyl 2-(1-bromoethyl)cyclopropanecarboxylate was isolated from the reaction mixture obtained by treatment of combination of crotyl bromide and 3-bromo-1-butene (molar ratio 1.63) with ethyl diazoacetate and a catalytic amount of $Rh_2(OAc)_4$. Geometrical isomers were not separable by GC analyses: ^1H NMR ($CDCl_3$) δ 4.15 and 4.13 (q, J = 7.1 Hz, CH_2O), 3.87–3.43 (quintet, CHBr), 1.78 and 1.76 (d, J = 6.7 Hz, $CHCH_3$), 1.81–0.60 (m, 4 H), 1.26 and 1.25 (t, J = 7.1 Hz, CH_3CH_2O). The isomer ratio of the isolated product was 1.2.

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Registry No. 4a, 10152-76-8; **4b**, 2155-94-4; **4c**, 2588-79-6; (*E*)-**4d**, 51752-08-0; (*E*)-**4e**, 42817-44-7; **5a**, 71031-93-1; **5b**, 66917-63-3; **5c**, 66917-65-5; **5d** (isomer 1), 79373-05-0; **5d** (isomer 2), 79373-06-1; **5e** (isomer 1), 79357-14-5; **5e** (isomer 2), 79357-15-6; **5** (X = I), 79357-16-7; **5** (X = Br), 39149-86-5; **5** (X = Cl), 29119-70-8; *cis*-**6** (X = Br), 79357-17-8; *trans*-**6** (X = Br), 38506-15-9; *cis*-**6** (X = Cl), 79357-18-9; *trans*-**6** (X = Cl), 79357-19-0; **7** (X = Br), 78331-59-6; **8** (X = Br), 79357-20-3; **8** (X = Cl), 79357-21-4; **9** (isomer 1), 79357-22-5; **9** (isomer 2), 79357-23-6; (*E*)-**10**, 79357-24-7; *trans*-**11**, 79357-25-8; *cis*-**11**, 79390-68-4; ethyl diazoacetate, 623-73-4; allyl iodide, 556-56-9; allyl bromide, 106-95-6; allyl chloride, 107-05-1; diethyl diazomalonate, 5256-74-6; (*E*)-crotyl bromide, 29576-14-5; ethyl 2-(1-bromoethyl)cyclopropanecarboxylate, 79357-26-9; 3-bromo-1-butene, 22037-73-6; $Rh_6(CO)_{16}$, 28407-51-4; $Rh_2(OAc)_4$, 15956-28-2; $CuCl\cdot P(O\text{-}i\text{-}Pr)_3$, 78955-42-7; $Cu(acac)_2$, 13395-16-9.

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Occurrence of the S_N(ANRORC) Mechanism in the Hydrazination of 1,2,4,5-Tetrazines[1-3]

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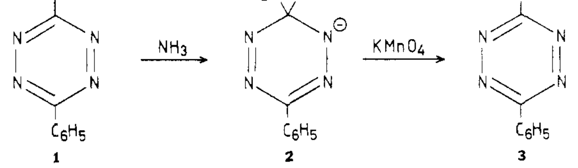
3-Alkyl(aryl)-1,2,4,5-tetrazines (7) when treated with hydrazine hydrate were found to undergo a Chichibabin hydrazination into 3-alkyl(aryl)-6-hydrazino-1,2,4,5-tetrazines (8) according to an S_N(ANRORC) mechanism. ^1H and ^{13}C NMR measurements indicate that the first step in this reaction sequence is the formation of a homoaromatic σ adduct anion, due to attack at C_6, and that the second step is the formation of an open-chain intermediate. With ^{15}N-labeled hydrazine, part of the label is found in the 1,2,4,5-tetrazine ring of the 6-hydrazino compounds 8*. NMR evidence is obtained which shows that the hydrazino compounds with the ^{15}N-label in the ring (8*II) and with the ^{15}N-label in the hydrazino group (8*I) are formed according to the S_N(ANRORC) mechanism. Treatment of 6-amino- or 6-halogeno-1,2,4,5-tetrazines with hydrazine leads to introduction of a hydrazino group at position 6. During this hydrazino deamination and hydrazino dehalogenation part of the molecules were found to react according to the S_N(ANRORC) mechanism, the other part followed the S_N(AE) pathway.

In a preceding paper[1] we obtained firm evidence that the anion of 6-amino-1,6-dihydro-3-phenyl-1,2,4,5-tetrazine (2), formed upon addition of ammonia to 3-phenyl-1,2,4,5-tetrazine (1, Scheme I), is homoaromatic. This σ adduct is in the homotetrazole conformation, containing 6 π electrons in the tetrazole ring and holding the amino group in the exo position and the hydrogen at the sp^3

Scheme I



1 2 3

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(1) Part 5 on 1,2,4,5-tetrazine and its derivatives. For part 4 see: Counotte-Potman, A.; van der Plas, H. C.; van Veldhuizen, A. *J. Org. Chem.*, in press.

(2) Part 30 on NMR investigations of σ adducts of heterocyclic systems with nucleophiles. For part 29 see: van den Haak, H. J. W.; van der Plas, H. C.; van Veldhuizen, A. accepted for publication in *J. Heterocycl. Chem.*

(3) Part 28 on the S_N(ANRORC) mechanism. For part 27 see: Kos, N. J.; van der Plas, H. C. *J. Org. Chem.* **1980**, *45*, 2942.

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