bridge protons), 2.00 ppm br (β-vinyl methyl), and the usual ethoxyl resonances.

Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.15; H, 7.37; O, 19.49. Found: C, 72.83; H, 7.38, O, 19.72.

The more polar product **8c** had ir bands at 1720, 1690, 1635 cm^{-1}; λ_{max} 235, 330 nm (ε 11800, 68); NMR signals at 6.90 br (β-vinyl proton), 5.9c (two vinyl protons), 1.7 ppm br (α-vinyl methyl), and the usual ethoxyl resonances.

Anal. Calcd for $C_{15}H_{18}O_3$: C, 73.15; H, 7.37, O, 19.49. Found: C, 72.89; H, 7.51; O, 19.49.

Catalytic Reduction of 12a and 12b. A solution of 2 g of **12a** in 30 ml of ethyl acetate was hydrogenated for 24 hr in the presence of 0.2 g of Pd/C. Filtration, evaporation at reduced pressure, and recrystallization from ether–hexane afforded **14a** in quantitative yield: mp 60–61°; ir band at 1720 cm^{-1}; NMR signals at 3.65 (2 H, epoxidic protons), 3.15 m (proton at ring junction), 1.58 ppm m (methylenes).

Anal. Calcd for $C_{10}H_{12}O_3$: C, 66.65; H, 6.71; O, 26.64. Found: C, 66.75; H, 6.77; O, 26.37.

Reduction of **12b** in the same fashion and recrystallization of the crude product from hexane afforded **14b**, mp 53–54°, ir band at 1720 cm^{-1}. The same substance was obtained by chromotography of **14a** over alumina and elution with chloroform.

Anal. Calcd for $C_{10}H_{12}O_3$: C, 66.65; H, 6.71; O, 26.64. Found: C, 67.00; H, 6.70; O, 26.30.

Reactions of 12 and 14 with Base. Reaction of **12a** with base under the conditions described for **4a, 4b, 7a,** and **7b** resulted in recovery of starting material **12a** and **12b**; hence excess base was employed. To a solution of 1.0 g of **12a** in 30 ml of 95% ethanol was added with stirring at ice bath temperature (nitrogen atmosphere) 15 ml of 10% sodium hydroxide solution. After 20 min, the mixture was diluted with water, acidified with HCl, and filtered. Methylation of the brown solid **13a** with diazomethane in the usual fashion afforded 0.9 g of **13b**, mp 183° (lit.[13] mp 183.5°). Treatment of **12b** with base followed by methylation also gave **13b** in 90% overall yield.

Reaction of **14a** or **14b** with base in the manner described in the previous paragraph followed by methylation of the crude product with diazomethane gave **15** in 90% yield, mp 170–171° (lit.[14] mp 171°, 172°).

Photocyclization of 5a. A solution of 0.5 g of **5a** in 50 ml of methanol was irradiated for 20 hr in a photochemical reactor with a Hanovia 450 lamp using a Pyrex filter. The solution was evaporated at reduced pressure and the residue chromatographed over 20 g of alumina. Elution with benzene afforded 0.45 g of noncrystalline **6**: ir band at 770 cm^{-1} (strained cyclopentanone); λ_{max} 285 nm (ε 68); NMR signals at 4.20 q (2 H) and 1.28 t (3 H, J = 7 Hz, ethoxyl), 2.2–3 ppm c (9 H, methinyl and methylene protons).

Anal. Calcd for $C_{13}H_{14}O_3$: C, 71.54; H, 6.47; O, 21.99. Found: C, 71.25; H, 6.40; O, 21.80.

Decarboxylation of 9a. Decarboxylation was achieved by heating the substance in a slow stream of nitrogen at 150° for 15 min until CO_2 evolution had ceased. Trituration of the product (**10**) with methanol resulted in crystallization. The material, mp 103°, was homogeneous on TLC, and had significant NMR signals at 7.60 dd (J = 6 Hz, 3, β proton) and 6.30 ppm dd (J = 6 Hz, 2, α proton).

Anal. Calcd for $C_{11}H_{12}O$: C, 87.46; H, 7.55. Found: C, 82.78; H, 7.51.

A solution of 0.1 g of **9a** in 3 ml of $CDCl_3$ was mixed with 2 ml of D_2O and stirred thoroughly. After 15 min, a portion of the mixture was transferred to an NMR sample tube; the NMR spectrum exhibited no OH absorption. The mixture was dried by addition of anhydrous sodium sulfate, filtered, and evaporated. The residue (**9b**) was pyrolyzed as described in the preceding paragraph. The NMR spectrum of the crude product (**10b**) now displayed the β- and α-cyclopentenone protons as doublets at 7.60 and 6.30 ppm (J = 6 Hz). On thin layer examination, **10b** exhibited R_f values identical with those of **10a**.

Registry No.—**4a,** 15052-12-7; **4b,** 15052-13-8; **5a,** 56689-06-6; **5b,** 56689-07-7; **5c,** 56689-08-8; **6,** 56689-09-9; **7a,** 56711-55-8; **7b,** 56711-56-9; **8a,** 56689-10-2; **8b,** 56689-11-3; **8c,** 56689-12-4; **9a,** 56689-13-5; **10a,** 56689-14-6; **11,** 35043-92-6; **12a,** 56689-15-7; **12b,** 56711-57-0; **14a,** 56689-16-8; **14b,** 56711-58-1.

References and Notes

(1) Supported in part by grants from the National Science Foundation (GP-12582) and the donors of the Petroleum Research Fund, administered by the American Chemical Society.

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(3) R. P. Linstead, *J. Chem. Soc.*, 1603 (1930).

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Epoxydiazo Ketones. Synthesis and Reactions

Neil F. Woolsey* and Mohammed H. Khalil

Department of Chemistry, University of North Dakota, Grand Forks, North Dakota 58202

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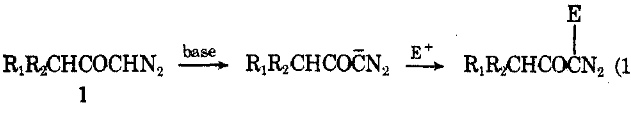
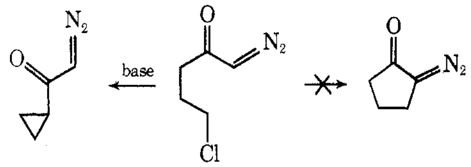
Darzens condensation of 3-chloro-1-diazopropanone with nonenolizable aldehydes and base in equal molar amount yielded 1-diazo-4-R-3,4-epoxy-2-butanones (**7**) [**a**, R = Ph; **b**, R = 4-$NO_2C_6H_4$; **c**, R = 4-$CH_3OC_6H_4$; **d**, R = (*E*)-PhCH=CH; **e**, R = 2-thienyl]. Under conditions of higher base and excess aldehyde molar ratios, **7** and diadducts of 2-diazo-1,5-di-R-4,5-epoxy-1-hydroxy-3-pentanones (**8**) were produced. The reactions of **7a–c** with hydrogen chloride gas in ether generated α-chloro ketones and opened the epoxide ring in the case of **7a** and **7c**. Photolysis of **7a** in methanol gave methyl 4-hydroxy-4-phenyl-2-butenoate (**32**). Pyrolysis of **7a** in refluxing methanol gave 1,1-dimethoxy-4-phenyl-3-buten-2-one (**34**).

Previous work has established that diazomethyl ketones undergo a variety of base-catalyzed reactions in a nondestructive manner[1], i.e., the diazo ketone moiety is maintained in the products. For the most part these reactions result from the facile formation of an anion at the diazomethyl carbon followed by reaction with electrophile (reaction 1).



$$\underset{\mathbf{1}}{R_1R_2CHCOCHN_2} \xrightarrow{\text{base}} R_1R_2CHCO\bar{C}N_2 \xrightarrow{E^+} R_1R_2CHCO\overset{E}{\overset{|}{C}}N_2 \quad (1)$$

In cases where anion formation could take place at either the diazomethyl or the 3 carbon, the greater acidity of the diazomethyl hydrogen directed condensation to this position. Only one case has been reported where reaction occurs at the 3 carbon, that of the 5-chloro-1-diazo-2-pentanone (3), where apparently favorable entropy factors and the greater reactivity of the 3-carbon anion make formation of 2 preferred over 4.[1f]



2 3 4

We have attempted to find structural factors which will direct reaction to the 3 carbon of diazomethyl ketones. Substitution of a phenyl group on carbon 3, however, did not increase the acidity of the 3-carbon hydrogen sufficiently to allow reaction of that center.[1d] Aldol reaction of 1 (R_1 = Ph; R_2 = H) took place at the diazo carbon exclusively.

This report contains our success in directing reaction to carbon 3 by substitution of a chlorine (1, R_1 = Cl; R_2 = H) at that carbon. This allows further reaction of the initial aldol adduct to form epoxydiazomethyl ketones, overall a Darzens condensation. The reactions of these novel compounds under acidic, thermal, and photochemical conditions were also examined.[1e,f,2]

Results and Discussion

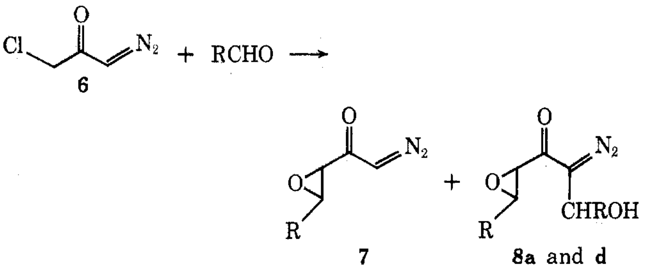
Base-Catalyzed Reaction. Treatment of the ω-chlorodiazomethyl ketone 3 with sodium hydroxide and benzaldehyde diverted reaction from formation of the intramolecular product 2 to the aldol product 6-chloro-2-diazo-1-hydroxy-1-phenyl-3-hexane (5). This indicated that formation of 2 in the absence of aldehyde resulted from the special properties of 3 and not an inversion in acidity of the diazomethyl and the 3-carbon hydrogen.

$$3 + \mathrm{PhCHO} \xrightarrow{^{-}\mathrm{OH}} \underset{\mathbf{5}}{\mathrm{Cl(CH_2)_3COCN_2CHOHPh}}$$

A real competitive increase in acidity of the 3-carbon hydrogen was observed, however, with 3-chloro-1-diazopropanone (6) and led to a general synthesis of epoxydiazo ketones 7.[2] By control of conditions, with certain aldehydes, only 7 or a mixture of 7 with the aldol product was formed (Scheme I).

When chlorodiazo ketone 6 was treated with equal molar amounts of benzaldehyde in methanol and aqueous sodium hydroxide solution, 1-diazo-3,4-epoxy-4-phenyl-2-butanone (7a) was formed in 69% yield. The analytical and spectral data were all consistent with this structural assignment (cf. Experimental Section). The size of the coupling constant (J = 1.5 Hz) for the epoxymethine protons supports trans stereochemistry for the epoxide ring.[3] Thus, the behavior of 6 is entirely comparable to Darzens condensation of chloroacetone.[4]

Scheme I



6 7 8a and d

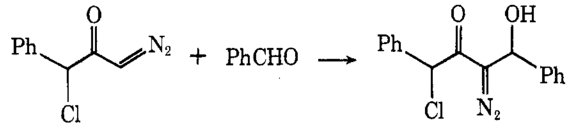
a, R = C_6H_5 (69%)
b, R = 4-$NO_2C_6H_4$ (88%)
c, R = 4-$CH_3OC_6H_4$ (35-55%)
d, R = $C_6H_5CH{=}CH$ (40%)
e, R = 2-thienyl (61%)

The scope of the reaction is exemplified by reaction of 6 with the aldehydes shown in Scheme I in the indicated yields. Attempts to extend reaction to *o*-phthalaldehyde and glucose have so far proved unrewarding. No other aldehydes having α hydrogens have been investigated.

When 6 was treated with a moderate molar excess of sodium hydroxide and a large excess of benzaldehyde, two products were isolated. The epoxydiazo ketone 7a and a diastereomeric mixture of 2-diazo-1,5-diphenyl-4,5-epoxy-1-hydroxy-3-pentanone (8a) were formed in 44 and 41% yields, respectively. Separation of the diastereomeric mixture was effected by fractional crystallization to give two isomers. The NMR spectral properties of the mixture and of the pure isomers were identical except for one epoxymethine proton which differed for the two isomers. Further confirmation of the diadduct nature of 8a was supplied by the basic retro-aldol cleavage[5] of the diastereomeric mixture of 8a, and both pure isomers to give 7a in 87–91% yield.

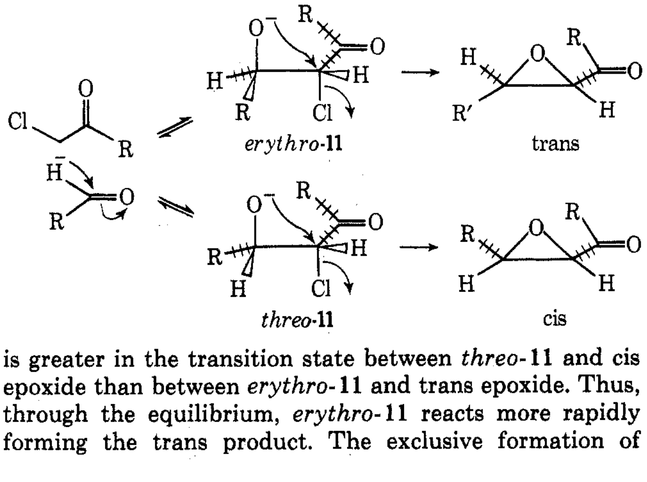
A diastereomeric mixture 8d of the diadduct of (*E*)-cinnamaldehyde and 6 was isolated by a similar procedure in 49% yield. No attempt was made to separate the component stereoisomers of 8d. The structural assignment was made on the basis of analogy to 8a, on the physical data, and the fact that this mixture was also cleanly cleaved to the Darzens product 7d by aqueous base in 70% yield. Undoubtedly the diadducts of other aldehydes could also have been prepared but these reactions were not attempted.

In contrast to the ready Darzens condensation of 6 with aldehydes, 3-chloro-1-diazo-3-phenyl-2-propanone (9) underwent only aldol condensation with benzaldehyde and aqueous sodium hydroxide solution. The oily product, a diastereomeric mixture of 1-chloro-1,4-diphenyl-4-hydroxy-2-butanone (10), was characterized spectroscopically.



9 10

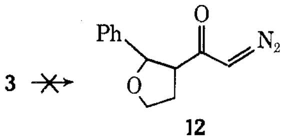
Mechanism of Base-Catalyzed Condensation. The mechanism postulated for the Darzens condensation[4b] to explain the observed stereospecificity involves initial aldol condensation of the chloro ketone anion with the aldehyde to form a keto halohydrin intermediate (or its anion). This can occur in two distinct ways to form *erythro*-11 and *threo*-11. Steric hindrance between the substituent groups



is greater in the transition state between *threo*-11 and cis epoxide than between *erythro*-11 and trans epoxide. Thus, through the equilibrium, *erythro*-11 reacts more rapidly forming the trans product. The exclusive formation of trans epoxides from **6** and aldehydes supports a similar interpretation for reaction of this chlorodiazo ketone.

The substituent effects observed for Darzens condensation of phenacyl chloride and para-substituted benzaldehydes[6] are also consistent with more facile reaction of electron-poor aldehydes. The relative yields of **7a**, **7b**, and **7c** support a similar trend for the reactivity of **6**. The yield of **7c** also increased from 35 to 55% on tripling the reaction time, consistent with this interpretation.

The lack of irreversible formation of **12** and **13** from **3** and **9**, respectively, with benzaldehyde probably reflects the steric interaction of disubstitution at one α carbon on the other observed previously.[1b] Diazo ketones of the general type $RR'CHCOCHN_2$ do not form aldol products nearly as readily as monosubstituted diazo ketones. Low equilibrium concentration of the aldol intermediates does not allow subsequent cyclization to **12** and **13**.



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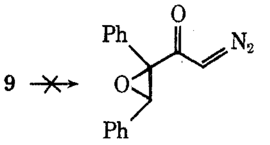
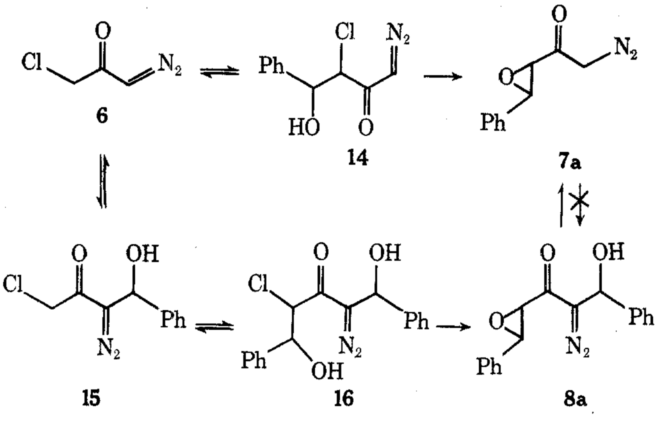


13

The effect of base and benzaldehyde molar ratios on formation of the mono- and diadducts was also investigated. The diazo carbon proton in **6** was more acidic than the chloromethylene protons as demonstrated by the deuterium exchange (D_2O and Na_2CO_3) exclusively at the diazo carbon. Thus, when equal molar amounts of **6**, base, and benzaldehyde are allowed to react, initial establishment of the aldol equilibrium at the diazo carbon forming **15** seems most likely (see Scheme II). Slower reaction of **6** at the chloromethylene carbon by the Darzens condensation via a low equilibrium concentration of **14** would siphon off **6**, converting it irreversibly to **7a**, which is stable to base. Once **7a** is formed, it can not undergo aldol reaction to form **8a** as treatment of **7a** under the reaction conditions showed. This result is consistent with the hindering of aldol reaction at one α carbon by disubstitution at the other discussed above. Some of the **7a** formed, however, could come from Darzens condensation of **15** to the diadduct **8a** via **16** in an irreversible reaction followed by retro-aldol at the diazo carbon to form **7a**. Both paths to **7a** must be operating. Isolation of a 4% yield of the diadduct **8a** worked up after a short period of time supports this view.

Scheme II

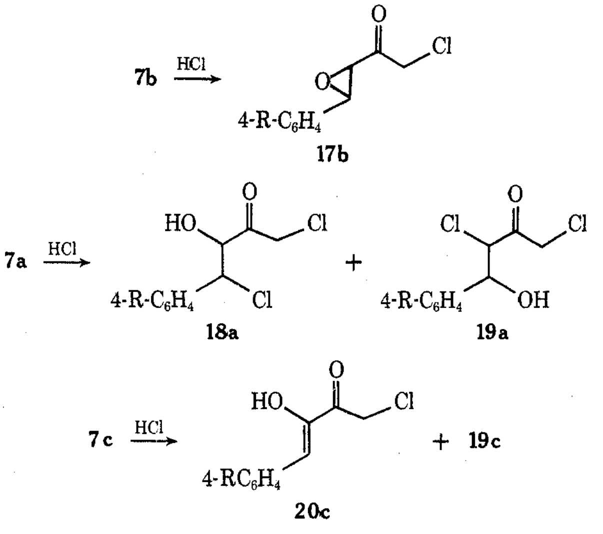


When **6** was treated with a moderate excess of base and a large excess of benzaldehyde, the retro-aldol reaction of **8a** to **7a** became unimportant, a contention supported by the lack of cleavage of **8a** under these reaction conditions. Some retro-aldol reaction of **15** to **6** probably occurs in order for the formation of **7a** to compete with the initial formation of **15**. Both **7a** and **8a** are then formed by irreversible reactions and cannot be interchanged, a contention consistent with the invariance in the **7a**/**8a** ratio with time. No evidence for the presence of **14**, **15**, or **16** could be found nor can the possibility of a **14** ⇄ **16** equilibrium be assessed at this time.

The lack of retro-aldol reaction of **8a** when benzaldehyde is in excess of hydroxide implies that the predominant base is the anion formed by addition of hydroxide to benzaldehyde. This base is strong enough to allow the **6** ⇄ **15** equilibrium and the Darzens condensation to take place but not for the cleavage of **8a** to **7a**. The basis for this selectivity is not clear.

Reactions with Hydrogen Chloride. In order to ascertain if the diazo group and the epoxy group would react independently or if some intramolecular interaction would take place, the diazo ketones **7a**, **7b**, and **7c** were treated with hydrogen chloride gas in anhydrous ether. The results are summarized in Scheme III. The *p*-nitrophenylepoxydiazo ketone **7b** reacted only at the diazo carbon to give 1-chloro-3,4-epoxy-4-(4'-nitrophenyl)butanone (**17b**).[2]

Scheme III



a, R = H b, R = NO_2 c, R = CH_3O

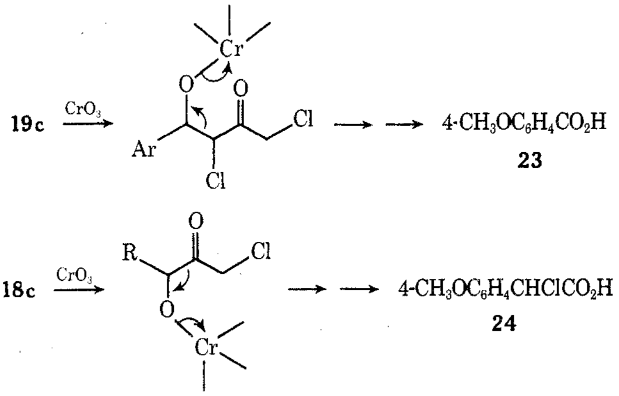
The phenylepoxydiazo ketone **7a** reacted with hydrogen chloride to form 1,4-dichloro-3-hydroxy-4-phenyl-2-butanone (**18a**) as the major product and the isomer 1,3-dichloro-4-hydroxy-4-phenyl-2-butanone (**19a**) as a minor by-product, although the latter could not be isolated but was identified spectroscopically in the mixture. The reaction of **7c** with hydrogen chloride gave mainly 1,3-dichloro-4-hydroxy-4-(4'-methoxyphenyl)-2-butanone (**19c**) with a smaller amount of 1-chloro-3-hydroxy-4-(4'-methoxyphenyl)-3-buten-2-one (**20c**). Neither **18a** nor **19c** gave satisfactory elemental analyses, probably because of their unstable nature and the time necessary to obtain analytical data. They did have sharp melting points and satisfactory parent ions in their mass spectra, however, consistent with the assigned molecular formula.

The structure of **18a** is based on the presence of $PhCHCl^+$ ions in its mass spectrum which is consistent with cleavage of structure **18a**. Furthermore, Jones oxidation[7] of **18a** gave chlorophenylacetic acid (**21**) and chloroacetic acid (**22**) in 68 and 67% yields, respectively. When a mixture of **18a** and **19a** was oxidized, the NMR spectrum of the reaction mixture contained peaks other than those of

$$\mathbf{18a} \xrightarrow{CrO_3} \underset{\mathbf{21}}{PhCHClCO_2H} + \underset{\mathbf{22}}{CH_2ClCO_2H}$$

21 and **22**, strongly suggesting that **19a** was isomerically rather than diastereomerically related to **18a**.

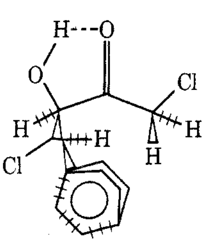
Jones oxidation of the *p*-methoxy derivative **19c**, however, resulted in cleavage to 4-methoxybenzoic acid (**23**). Although spectroscopic evidence was adduced for the other fragment, chloropyruvic acid, it was not isolated. This distinguished structure **19c** from its isomer **18c**. The latter should be oxidized to **24** instead of **23** as with the oxidation of **18a** to **21**.



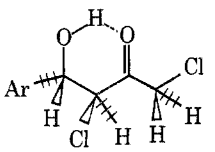
Another line of evidence supporting structure **19c** comes from a comparison of the NMR spectra of **18a**, **19a**, and **19c** given in Table I. Note that the CHOH and CHCl absorptions are quite similar in all three compounds but that in **18a** the two CH_2Cl protons are nonequivalent whereas they are equivalent in **19a** and **19c**. Furthermore, one of these protons in **18a** has roughly the same chemical shift as those in **19a** and **19c**, whereas the other CH_2Cl proton is shielded by 0.50 ppm. This difference can be rationalized if one considers the intramolecular hydrogen bonded form of the hydroxy ketone portion of the structure (the diastereomers shown are those predicted for stereospecific opening of the trans epoxides). In the case of **18a** one conformation allows the phenyl moiety to come close to the CH_2Cl group. Partially restricted rotation as well as some conformation preference could readily explain the shielding of one CH_2Cl proton. In the case of **19a** and **19c**, however, the hydroxy ketone hydrogen bond holds the aromatic ring away from the CH_2Cl group and provides no basis for shielding. Thus, the CH_2Cl protons in **19a** and **19c**, should be equivalent, as was found.

Table I
Chemical Shifts (δ, ppm)

Proton	18a	19a	19c
CHOH	4.75	4.72	4.70
CHCl	5.20	5.45	5.38
CH_2Cl	4.33, 3.83	4.38	4.35

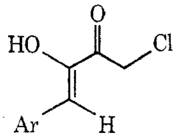


18a

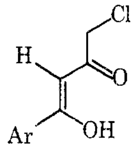


19a, Ar = Ph
c, Ar = 4-$CH_3OC_6H_4$

The structure assigned the minor product from hydrogen chloride reaction of **7c** is based on a detailed consideration of the physical data. Basically, the mass spectrum, the elemental analysis, and spectral data restrict consideration to structures **20c**, **25**, and **26**. The vinyl and hydroxyl absorptions at δ 6.39 and 6.9 ppm (the latter was under part of the aromatic absorption) respectively argue against structures **25** and **26**. The hydroxyl proton of **25** and **26** should appear near δ 15 ppm;[1d,8,9] the vinyl proton of **26** would be expected near δ 8 ppm.[9] The infrared spectrum of **20c** showed typical enolic hydroxyl adsorption at 2.91 μ[10] but the hydroxyl absorption of **25** and **26** would be expected at longer wavelengths.[1d,11] The ultraviolet spectrum of **20c** showed two maxima at 235 (ε 7060) and 343 nm (ε 25000) which shifted to 245 (ε 10000) and 383 nm (ε 14500) on addition of sodium hydroxide solution. This behavior, particularly the bathochromic shift on addition of base, is typical of an enolic α-diketone[12] but inconsistent with a β-diketone.[13] The mass spectrum of **20c** showed, in addition to a parent ion containing one chlorine atom, a base peak at *m/e* 121 and a weak peak at *m/e* 149. These peaks are consistent only with structure **20c** in the diketo form.



20c



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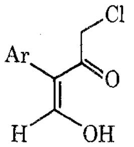

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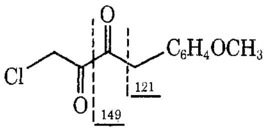
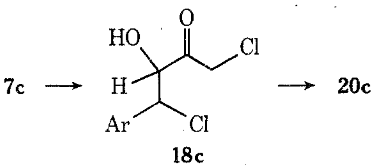


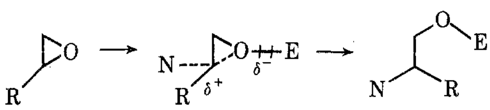
The structure assigned **20c** also supports the structure assigned **19c**. The mechanism of formation of **20c** (reaction 2) could reasonably involve initial formation of isomer **18c**



18c (2)

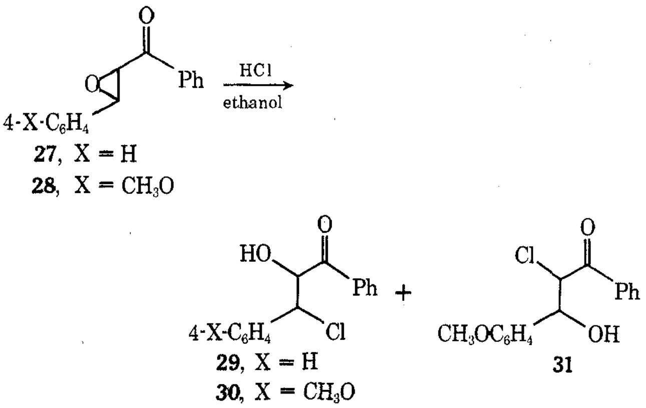
followed by elimination of hydrogen chloride to **20c**. If **19c** was diastereomeric with **18c**, then it is difficult to see why **19c** would also not be unstable and give rise to **20c**. Therefore, **19c** and **18c** must be isomeric. Furthermore, treatment of **19c** with base gave a mixture which did not contain the characteristic NMR spectral peaks of **20c**.

Mechanistically the formation of **18a** with **19a** from **7a** with hydrogen chloride in ether is understandable in terms of the push-pull mechanism postulated for epoxide ring opening (reaction 3).[14] The transition state under acidic conditions is characterized by partial bond formation to an electrophile (E) and with a nucleophile (N) simultaneously with former predominating. R groups which allow dispersion of the partially developed positive charge tend to favor epoxy ring opening at that carbon under acidic conditions. Thus, product **18a** is the expected isomer on this basis from **7a**.



(3)

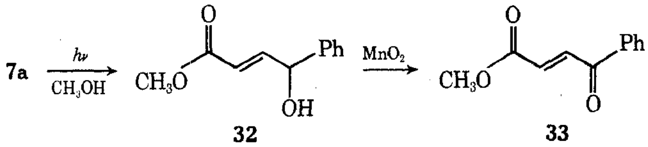
The major production of **19c** from **7c**, however, is not consistent with this interpretation. A similar result has been observed before. In the case of **27** and **28**, **27** gave rise only to **29**[15] when treated with hydrogen chloride in ethanol, while the *p*-methoxyl series **28** gave both **30** and **31** although the yields were not reported.[16] In view of the fact that the push–pull mechanism was derived from reactions of aryl epoxides,[14] not aryl acyl epoxides, and because of the dearth of examples of reactions in the literature other than those above, it seems imperative that further investigation of such systems be made before more definitive mechanistic conclusions may be drawn.



27, X = H
28, X = CH$_3$O
29, X = H
30, X = CH$_3$O
31

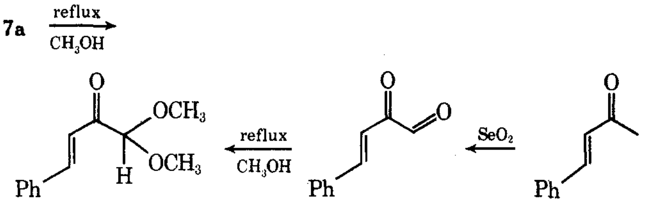
The apparent relative reactivity of the epoxy and diazo functions and the observed products indicate that the diazo group probably reacts first followed by independent reaction of the epoxide ring. Under aqueous conditions this is apparently not true.[2a]

Photo and Thermal Decomposition. Irradiation of the epoxydiazo ketone **7a** in methanol gave methyl 4-hydroxy-4-phenyl-2-butenoate (**32**) as a brown liquid in 62% yield.[2b] Confirmation of structure **32** came from the manganese dioxide oxidation of the allylic hydroxyl group to the known[17] methyl 4-oxo-4-phenyl-2-butenoate (**33**) in 74% yield.



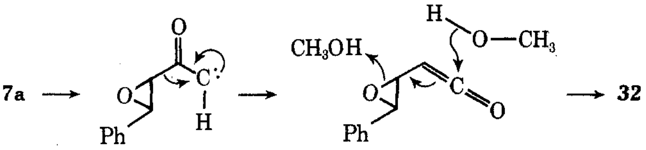
32 **33**

Pyrolysis of **7a** in refluxing benzene gave an intractable red oil.[2b] Refluxing in methanol over 48 hr, however, gave an 83% yield of 1,1-dimethoxy-4-phenyl-3-buten-2-one (**34**). The keto acetal **34** was synthesized from 4-phenyl-3-buten-2-one (**36**) by selenium dioxide oxidation[18] to the 4-phenyl-2-oxo-3-butenal (**35**) followed by refluxing in methanol, thus confirming the structural assignment.



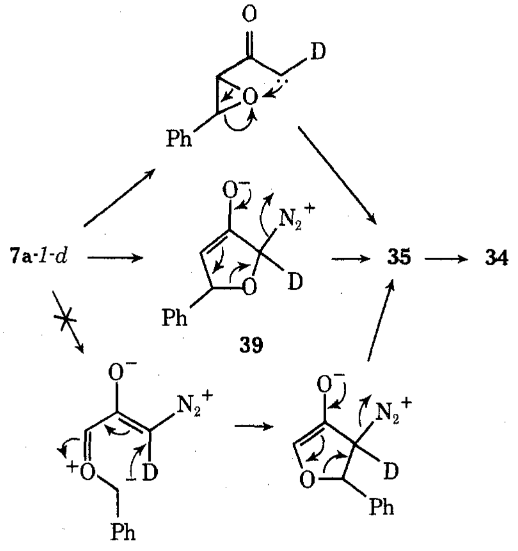
34 **35** **36**

Mechanistically the photochemical reaction of **7a** probably proceeds by normal Wolff rearrangement[19] via the ketocarbene **37** to the epoxy ketene **38**. Nucleophilic attack by methanol on **38** could open the epoxide as shown to give the observed product **32**. An epoxy ketene has been isolated by others[2b] on irradiation of **7a** in a hydrocarbon matrix at low temperature, supporting this mechanism.



37 **38**

Scheme IV

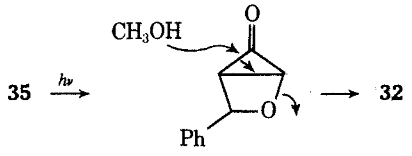


39 **40** **41**

The mechanism of the thermal rearrangement probably involves initial formation of **35** followed by acetal formation in refluxing methanol. The rearrangement of **7a** to **35** could be brought about by direct intramolecular abstraction of oxygen by a thermally generated ketocarbene[20] or by cyclization before loss of nitrogen to **39** followed by ring opening concerted with nitrogen loss to **35** (Scheme IV).[21] Both mechanisms are consistent with the results of a deuterium labeling experiment where the diazo carbon hydrogen of **7a** was replaced with deuterium.[22] Pyrolysis of **7a-*1-d*** in methanol *O-d* gave **34-*1-d*** with no change in deuterium content. This result eliminates the carbon–carbon epoxide ring cleavage mechanism observed for vinyl oxiranes[23] which would have given **34-*3-d*** for rearrangement of **7a** via **40** and **41** (Scheme IV).

If both the thermal and photochemical reactions proceeded through the ketocarbene **37** it is difficult to see why the products are different unless the multiplicity of the carbene generated in the two ways is different.[24] The Wolff rearrangement normally takes place through a singlet carbene.[25] If the thermal reaction took place through a triplet ketocarbene, then irradiation of **7a** with a triplet sensitizer should give high yields of the thermal product **34** or **35**.[26] Irradiation of **7a** with benzophenone as sensitizer gave a mixture which lacked the characteristic peaks of **32**, **34**, or **35**. This result implies that neither **32** nor **35** is formed through a triplet ketocarbene.

It is possible that **35** is a common intermediate in both thermal and photo processes. Formation of **32** could take place by rapid secondary irradiation of **35** through an intramolecular Paterno–Büchi reaction[27] (reaction 4) followed by opening of the cyclopropanone intermediate as indicated to form **32**. Irradiation of **35** in methanol gave an intractable mixture, however, which lacked the characteristic peaks of **32** in the NMR spectrum.



(4)

Thus, the most probable mechanism for the photolysis of **7a** is the Wolff rearrangement through a singlet ketocarbene. The pyrolysis reaction probably occurs by cyclization to **39** prior to nitrogen loss followed by rearrangement to **35** and addition of methanol to **34**.

Experimental Section

General. Melting points were determined on a Fisher-Jones hot stage; ir spectra with a Beckman IR-12 or IR-33(i); NMR with a Varian A-60; mass spectra with a CEC 491; uv spectra with a Cary 14. Microanalyses were performed by Midwest Microlabs.

Diazomethane. Diazomethane was prepared from bis(*N*-methyl-*N*-nitroso)terephthalamide by a standard procedure.[28] The yield was estimated by standardization of an aliquot by the benzoic acid acid procedure.[28]

1-Chloro-3-diazopropanone (6). Literature preparation[29] of **6** from chloroacetyl chloride and diazomethane was followed by fractional vacuum distillation. After the first 40% was discarded (which contained an impurity, probably dichloroacetone), **6** was collected as a yellow oil (52%): bp 45–47° (1 mm); NMR (CCl_4) δ 5.90 (s, 1 H, CHN_2), 3.96 ppm (s, 2 H, CH_2Cl); ir (neat) 4.79 (m, $C{=}N_2$), 6.17 μ (s, C=O).

3-Chloro-1-diazo-3-phenyl-2-propanone (9). Literature preparation[30] of **9** from chlorophenyl acetyl chloride and diazomethane gave a 61% yield, recrystallized from ether–pentane: mp 60–61° (lit.[30] 62°); NMR δ 7.32 (s, 5 H, Ph), 5.65 (s, 1 H, CHN_2), and 5.18 ppm (s, 1 H, CHCl); ir ($CHCl_3$) 4.78 (s, $C{=}N_2$), 6.18 μ (s, C=O).

6-Chloro-2-diazo-1-hydroxy-1-phenyl-3-hexanone (5). To an ice-cold, stirred solution of 0.50 g (3.4 mmol) of **3**[1c] in 30 ml of methanol and 3 ml of benzaldehyde was added 0.14 g (3.4 mmol) of sodium hydroxide dissolved in 5 ml of water. After 20 min water was added, the mixture extracted with methylene chloride, the solvent distilled, and the residue chromatographed on alumina (activity II, 100 g). Elution with hexane removed starting material, with benzene gave 0.39 g (45%) of **5** as a yellow oil: NMR ($CDCl_3$) 7.40 (s, 5 H, Ph), 6.05 (s, 1 H, CHOH), 4.02 (br s, 1 H, CHOH), 5.08 (t, 2 H, CH_2Cl), 2.28–1.95 ppm (m, 4 H, $COCH_2CH_2$); ir (neat) 2.93 (w, OH), 4.75 (s, $C{=}N_2$), 6.18 μ (s, C=O).

1-Chloro-3-diazo-1,4-diphenyl-4-hydroxy-2-butanone (10). To an ice-cold, stirred solution of 0.5 g (2.6 mmol) of **9** in 30 ml of methanol and 3 ml of benzaldehyde was added 0.11 g (2.6 mmol) of sodium hydroxide dissolved in 4 ml of water. After stirring for 30 min, the mixture was poured into 30 ml of water and extracted thrice with 50-ml portions of methylene chloride. After removal of the solvent, the extract was chromatographed (basic alumina, activity II, 100 g). Elution with carbon tetrachloride and benzene gave unreacted benzaldehyde and **9**, respectively. Elution with ether–ethyl acetate (2:3) gave on solvent removal 0.39 g (25%) of a diastereomeric mixture of **10**: NMR (CCl_4) δ 7.35 (d, 10 H, 2 Ph), 5.93 (s, CHOH, isomer A), 5.09 (s, sum A + B = 1 H, CHOH, isomer B), 5.53 (s, CHCl, isomer B), 5.50 (s, sum A + B = 1 H, CHCl, isomer A), 4.22 ppm (br s, 1 H, CHOH); ir ($CHCl_3$) 2.93 (w, OH), 4.75 (s, $C{=}N_2$), 6.17 μ (s, C=O).

Darzens Reaction of Aldehydes with 6. General Procedure. To an ice-cold, stirred solution of 0.5 g (4.2 mmol) of **6** and 4.2 mmol of aldehyde in 20 ml of methanol was added 0.17 g (4.2 mmol) of sodium hydroxide in 4 ml of water. After stirring for 30 min, 50 ml of water was added, and the precipitate was filtered off and recrystallized from methanol–water.

1-Diazo-3,4-epoxy-4-phenyl-2-butanone (7a). Reaction of **6** with benzaldehyde gave 69% of **7a** as yellow crystals: mp 95–96°; NMR ($CDCl_3$) δ 7.33 (s, 5 H, Ph), 5.58 (s, 1 H, CHN_2), 3.91 (d, 1 H, J = 1.5 Hz, epoxymethine), 3.48 ppm (d, 1 H, J = 1.5 Hz, epoxymethine); NMR ($CDCl_3$, D_2O, Na_2CO_3) same as above except lacking δ 5.58 peak; ir ($CHCl_3$) 4.76 (s, $C{=}N_2$), 6.13 μ (s, CO); uv max (MeOH) 280 nm (ϵ 15600), 235 (20800); mass spectrum (30 eV, 90°) *m/e* (rel intensity) 188 (0.6, $C_{10}H_8O_2N_2$), 160 (5, P − N_2), 159 (12), 120 (12), 106 (39), 105 (100), 103 (11), 91 (12), 90 (11), 77 (11). Anal. Calcd for $C_{10}H_8O_2N_2$: C, 63.83; H, 4.25; N, 14.87. Found: C, 63.77; H, 4.52; N, 14.85. In a second run the reaction was terminated after 5 min, then the mixture was extracted with methylene chloride. After concentration, the crystalline precipitate was filtered off and recrystallized to give 33% of **7a**. The filtrate was chromatographed on Florisil (activity II, 20 g) eluted with hexane, which gave benzaldehyde and **6**, and with benzene–ether (9:1), which afforded 4% of the diastereomeric mixture of **8a**, mp 79–102°, identified by the characteristic NMR spectrum.

1-Diazo-3,4-epoxy-4-(4′-nitrophenyl)-2-butanone (7b). Reaction of **6** with 4-nitrobenzaldehyde gave 88% of **7b** as yellow crystals: mp 134–135°; NMR ($CDCl_3$) δ 8.13 (m, 2 H, 4′-nitrophenyl), 7.50 (m, 2 H, 4′-nitrophenyl), 5.82 (s, 1 H, CHN_2), 4.13 (d, 1 H, J = 1.5 Hz, epoxymethine), 3.50 ppm (d, 1 H, J = 1.5 Hz, epoxymethine); ir (Nujol) 4.78 (s, $C{=}N_2$), 6.18 μ (s, C=O). Anal. Calcd for $C_{10}H_7N_3O_4$: C, 51.52; H, 3.00; N, 18.02. Found: C, 51.28; H, 3.25; N, 17.95.

1-Diazo-3,4-epoxy-4-(4′-methoxyphenyl)-2-butanone (7c). Reaction of **6** with 4-methoxybenzaldehyde gave 30% of **7c** as a yellow solid: mp 83–84°; NMR ($CDCl_3$) δ 7.25 (m, 2 H, 4′-methoxyphenyl), 3.76 (s, 3 H, OCH_3), 3.88 (d, 1 H, J = 1.5 Hz, epoxymethine), 3.50 ppm (d, 1 H, J = 1.5 Hz, epoxymethine); ir (Nujol) 4.75 (s, $C{=}N_2$), 6.20 μ (s, C=O). Anal. Calcd for $C_{11}H_{10}N_2O_3$: C, 60.57; H, 4.58; N, 12.84. Found: C, 60.33; H, 4.80; N, 12.64. A second run as above except for the 1.5-hr reaction time gave a 55% yield of **7c**.

1-Diazo-3,4-epoxy-6-phenyl-5-hexen-2-one (7d). Reaction of **6** with (*E*)-cinnamaldehyde gave a 46% yield of **7d** as yellow crystals: mp 77–78°; NMR ($CDCl_3$) δ 7.33 (s, 5 H, Ph), 6.86 (d, 1 H, J = 16 Hz, PhCH=), 5.85 (dd, 1 H, J = 16, J' = 7.5 Hz, PhCH=CH–), 3.58 (dd, J' = 7.5, J'' = 2 Hz, =CHCHO–), 3.47 ppm (d over 3.58 dd, sum 2 H, J'' = 2 Hz, -COCHO–); ir (Nujol) 4.74 (s, $C{=}N_2$), 6.17 μ (s, C=O). Anal. Calcd for $C_{12}H_{10}N_2O_2$: C, 67.31; H, 4.67; N, 13.08. Found: C, 67.03: H, 4.82; N, 13.25.

1-Diazo-3,4-epoxy-4-(2′-thienyl)-2-butanone (7e). Reaction of **6** with 2-thiophene carboxaldehyde gave a 61% yield of **7e** as yellow crystals: mp 100.5–101.5°; NMR ($CDCl_3$) δ 7.18 (m, 4 H, thienyl), 5.56 (s, 1 H, CHN_2), 4.16 (d, 1 H, J = 1.5 Hz, epoxymethine), 3.65 ppm (d, 1 H, J = 1 Hz, epoxymethine); ir (Nujol) 4.75 (s, $C{=}N_2$), 6.17 μ (s, C=O). Anal. Calcd for $C_8H_6N_2O_2S$: C, 49.48; H, 3.11; N, 14.42; S, 16.51. Found: C, 49.37; H, 3.34; N, 14.22; S, 16.39.

Diadducts. 2-Diazo-1,5-diphenyl-4,5-epoxy-1-hydroxy-3-pentanone (8a). To an ice-cold, stirred solution of 0.50 g (4.2 mmol) of **6** and 2 ml of benzaldehyde in 20 ml of methanol was added 0.34 g (8.4 mmol) of sodium hydroxide dissolved in 8 ml of water. After stirring for 30 min, 30 ml of water was added and the solution extracted with three 50-ml portions of methylene chloride. After removal of the solvent, the residue was chromatographed on Florisil (activity II, 60 g). Elution with hexane gave unreacted starting materials; with carbon tetrachloride, the epoxydiazo ketone **7a** in 44% yield; with benzene–ether, the diadduct **8a** (0.50 g, 41%) as a diastereomeric mixture with mp 77–106°; NMR ($CDCl_3$) δ 7.35 (d, 10 H, 2 Ph), 6.12 (d, 1 H, CHOH), 4.25 (d, 1 H, CHOH), 4.10 (d, J = 1.5 Hz, epoxymethine, isomer A), 4.02 (d, sum of A + B = 1 H, J = 1.5 Hz, epoxymethine, isomer B), 3.70 ppm (d, 1 H, J = 1.5 Hz, epoxymethine); NMR ($CDCl_3$–D_2O) same as above except for δ 6.12 (s, 1 H, CHOD) and lacking the δ 4.25 ppm peak; ir ($CHCl_3$) 2.95 (w, OH), 4.77 (s, $C{=}N_2$), 6.19 μ (s, CO); mass spectrum (30 eV, 80°) *m/e* (rel intensity) 266 (36, $C_{17}H_{14}O_3$), 248 (40), 247 (37), 246 (25), 199 (10), 197 (10), 161 (10), 160 (81), 159 (10), 147 (10), 120 (21), 119 (19), 118 (84), 106 (34), 105 (37), 103 (23), 91 (100), 90 (15), 77 (21), 75 (13), 69 (11), 62 (94), 61 (37), 59 (10). Anal. Calcd for $C_{17}H_{14}O_3N_2$: C, 69.41; H, 4.76; N, 9.52. Found: C, 69.17; H, 4.78; N, 9.40.

Fractional crystallization of the diastereomeric mixture of **8a** from ether gave 80 mg of isomer A: mp 110.5–111.5°; NMR same as above except δ 4.10 integrated for one proton and lacked the δ 4.02 peak. The filtrate from isomer A crystallization was cooled in ether–hexane to give 120 mg of isomer B: mp 78.5–80°; NMR as above except the δ 4.02 peak integrated for one proton and lacked the δ 4.10 peak.

A second run with the same amounts of reagents was stirred for 90 min and worked up as before to give 0.30 g (37%) of epoxydiazo ketone **7a** and 0.44 g (36%) of the diastereomeric mixture of the diadducts **8a** identified by the NMR spectrum.

4-Diazo-6,7-epoxy-3-hydroxy-1,9-diphenyl-1,8-nonadien-4-one (8d). To an ice-cold, stirred solution of 0.50 g (4.2 mmol) of **6** and 2 ml of (*E*)-cinnamaldehyde in 30 ml of methanol was added 0.34 g (8.4 mmol) of sodium hydroxide dissolved in 8 ml of water. After 30 min, the precipitation of a solid was completed by addition of 30 ml of water. The solid was filtered and recrystallized from acetone to give 0.72 g (49%) of a diastereomeric mixture of **8d** as a yellow solid: mp 124–130°; NMR (Me_2SO) δ 7.60–5.9 (m, 15 H, 2 Ph, 4 vinyl, OH), 5.55 (d, 1 H, CHOH), 4.15–3.75 ppm (m, 2 H, epoxymethine); ir (Nujol) 2.94 (w, OH), 4.72 (s, $C{=}N_2$), 6.16 μ (s, C=O). Anal. Calcd for $C_{21}H_{18}O_3N_2$: C, 72.83; H, 5.20; N, 8.26. Found: C, 73.04; H, 5.36; N, 8.26.

Base Cleavage of 8a. To an ice-cold stirred solution of 200 mg (0.68 mmol) of the diastereomeric mixture of **8a** in 5 ml of methanol was added 0.35 ml of a 2 *M* (0.68 mmol) aqueous sodium hydroxide solution. After stirring for 15 min the precipitated solid was filtered to give 115 mg (90%) of **7a**, mp 95–96°.

When the above reaction was carried out with 0.5 ml of benzaldehyde added, followed by addition of water and extraction with methylene chloride, the NMR spectrum of the solvent-free reaction mixture showed only adsorptions due to benzaldehyde and the starting diastereomeric mixture **8a** but lacked the characteristic peaks of **7a.**

Cleavage of 8a, Isomer A. Treatment of 100 mg (0.34 mmol) of **8a** isomer A, with 0.17 ml of 2 *M* aqueous sodium hydroxide solution as above gave 55 mg (87%) of **7a,** mp 94.5–96°.

Cleavage of 8a, Isomer B. Treatment of 100 mg (0.34 mmol) of **8a,** isomer B, with 0.17 ml of 2 *M* sodium hydroxide solution as above gave 58 mg (91%) of **7a,** mp 95–96°.

Cleavage of 8d. Treatment of 0.50 g (1.4 mmol) of the diastereomeric mixture **8d** in 250 ml of methanol with 0.74 ml of 2 *M* sodium hydroxide solution followed by the above extractive work-up gave on concentration and crystallization from methanol–water 100 mg (70%) of **7d,** identified by mp (77–78°), mmp (77–78°), and NMR spectrum with an authentic sample.

Hydrogen Chloride Reactions of Epoxydiazo Ketones. 1-Chloro-3,4-epoxy-4-(4′-nitrophenyl)-2-butanone (17b). Dry hydrogen chloride gas was bubbled through a stirred solution of 250 mg (1.07 mmol) of **7b** in 250 ml of anhydrous ether. After 45 min the reaction mixture was washed with water, dried, and distilled to a solid residue which was crystallized from methanol–water to give 180 mg (71%) of **17b:** mp 101–102°; NMR ($CDCl_3$) δ 8.35 (m, 2 H, 4′-nitrophenyl), 7.52 (m, 2 H, 4′-nitrophenyl), 4.28 (s, 2 H, CH_2Cl), 4.21 (d, 1 H, *J* = 1.5 Hz, epoxymethine), 3.77 ppm (d, 1 H, *J* = 1.5 Hz, epoxymethine); ir ($CHCl_3$) 5.79 μ (s, C=O); mass spectrum *m/e* (rel intensity) 243 (2, $C_{18}H_8{}^{37}ClNO_4$), 241 (6, $C_{10}H_8{}^{35}ClNO_4$), 201 (6), 200 (34), 176 (6), 165 (6), 154 (9), 153 (10), 152 (100), 150 (12), 136 (52), 135 (81), 118 (9), 107 (12), 106 (14), 92 (10), 91 (6), 90 (11), 89 (19), 84 (16), 77 (30). Anal. Calcd for $C_{10}H_8ClNO_4$: C, 49.69; H, 3.31; N, 5.71; Cl, 14.70. Found: C, 49.41; H, 3.48; N, 5.88; Cl, 14.96.

Reaction of 7a with Hydrogen Chloride. A solution of 500 mg of **7a** in 30 ml of anhydrous ether was treated as above with hydrogen chloride gas for 10 min and worked up as above. The crude product was crystallized from ether–hexane, then from chloroform to give 330 mg (54%) of 1,4-dichloro-3-hydroxy-4-phenyl-2-butanone (**18a**): mp 100–101°; NMR δ 7.38 (s, 5 H, Ph), 5.20 (d, 1 H, *J* = 5 Hz, CHCl), 4.75 (br d, 1 H, C**H**OH), 4.33 (d, 1 H, *J* = 16 Hz, **H**CHCl), 3.83 (d, 1 H, *J* = 16 Hz, HC**H**Cl), 3.48 ppm (br, 1 H, CHO**H**); NMR ($CDCl_3$–D_2O) same as above except δ 4.75 (d, 1 H, *J* = 5 Hz, C**H**OD) and lacking the δ 3.48 peak; ir ($CHCl_3$) 2.83 (w, OH), 5.74 μ (s, C=O); mass spectrum (24 eV, 150°) *m/e* (rel intensity) 236 (0.47, $C_{10}H_{10}{}^{37}Cl_2O_2$), 234 (3, $C_{10}H_{10}{}^{35}Cl^{37}ClO_2$), 232 (5, $C_{10}H_{10}{}^{35}Cl_2O_2$), 128 (2.5), 127 (33, $C_7H_6{}^{37}Cl$), 126 (9), 125 (100, $C_7H_6{}^{35}Cl$), 120 (6), 119 (9), 91 (91). Anal. Calcd for $C_{10}H_{10}O_2Cl_2$: C, 51.53; H, 4.32; Cl, 30.42. Found: C, 50.71, 51.02; H, 4.68, 4.55; Cl, 30.55. Removal of solvent from the above filtrates gave 110 mg of the isomeric mixture of chlorohydrin **18a** and 1,3-dichloro-4-hydroxy-4-phenyl-2-butanone (**19a**) which could not be separated cleanly. The NMR of this mixture showed peaks due to **18a** and in addition had peaks of δ 5.45 (d, 1 H, *J* = 3 Hz, CHCl), 4.72 (br d, 1 H, C**H**OH), 4.38 (s, 2 H, CH_2Cl), 3.20 ppm (br, 1 H, CHO**H**); NMR ($CDCl_3$–D_2O) same as above except for δ 4.72 (d, 1 H, *J* = 3 Hz, C**H**OD) and lacking 3.20-ppm peak. The integral area ratio of the δ 5.20 peak of **18a** to the 5.45 peak of **19a** was 1:3. Total yield of **18a** was 58% and of **19a** was 13% based on the NMR ratio.

Reaction of 7c with Hydrogen Chloride. Treatment of 560 mg (2.6 mmol) of **7c** with hydrogen chloride as above gave a yellow oil which was crystallized from ether–hexane, then from ether. Filtration gave 320 mg (42%) of 1,3-dichloro-4-hydroxy-4-(4′-methoxyphenyl)-2-butanone (**19c**): mp 80–81°; NMR ($CDCl_3$) δ 7.41 (m, 2 H, 4′-methoxyphenyl), 6.88 (m, 2 H, 4′-methoxyphenyl), 5.37 (d, 1 H, *J* = 3 Hz, CHCl), 4.68 (d, 1 H, *J* = 3 Hz, C**H**OH), 4.33 (s, 2 H, CH_2Cl), 3.77 (s, 3 H, OCH_3), 3.20 ppm (br, 1 H, CHO**H**); ir ($CHCl_3$) 2.87 (w, OH), 5.80 μ (s, C=O); mass spectrum (70 eV, 50°) *m/e* (rel intensity) 264 (0.18, $C_{11}H_{12}O_3{}^{35}Cl^{37}Cl$), 262 (0.3, $C_{11}H_{12}O_3{}^{35}Cl_2$), 229 (4, $C_{11}H_{12}O_3{}^{37}Cl$), 227 (1.1, $C_{11}H_{12}O_3{}^{35}Cl$), 157 (14), 155 (38), 136 (24, $C_8H_8O_2$), 135 (38), 121 (100, C_8H_9O), 91 (14), 77 (29), 76 (10). Anal. Calcd for $C_{11}H_{12}Cl_2O_3$: C, 50.21; H, 4.60; Cl, 26.95. Found: C, 50.19; H, 4.83; Cl, 25.81, 25.55. In a second run 300 mg (1.38 mmol) of **7c** was treated with hydrogen chloride and worked up as before. Crystallization of the crude pale yellow oil from ether–hexane gave 50 mg of **20c** (16%), mp 103–108°. Recrystallization from benzene gave colorless crystals which turned yellow on drying in vacuo. When heated slowly the yellow crystals turned white and melted at 107–108°:[31] ir ($CHCl_3$) 2.91 (m, OH), 5.94, 6.10, 6.22 (m, m, s, enolic dicarbonyl), 6.59, 7.92, 8.48 μ; NMR (CCl_4) δ 7.73 (m, 2 H, 4′-$CH_3OC_6\mathbf{H}_4$), 6.8 (m, 3 H, 4′-$CH_3OC_6\mathbf{H}_4$ and –OH, latter removed on deuteration with D_2O), 6.38 (s, 1 H, vinyl), 4.43 (s, 2 H, CH_2Cl), 3.82 ppm (s, 3 H, CH_3O); uv (C_2H_5OH) max 234–237 (7060), 342–343.5 nm (25000), which changed to 244.5–246 (10600), 381–385 nm (14500) on addition of one drop of 3 *N* sodium hydroxide solution; mass spectrum (70 eV, 80°) *m/e* (rel intensity) 228 (6.8), 226 (19.5), 163 (4.4), 149 (8.6), 148 (3.1), 121 (100), 120 (3), 91 (5.4), 78 (4.9), 77 (6.4), 51 (5.7). Anal. Calcd for $C_{11}H_{11}O_3Cl$: C, 58.29; H, 4.89; Cl, 15.64. Found: C, 58.10; H, 5.05; Cl, 15.67.

Chromic Acid Oxidations of 18a. To a stirred solution of 150 mg of **18a** in 5 ml of reagent grade acetone was added 2 ml of a 1 *M* aqueous chromium trioxide solution containing 0.1 ml of concentrated sulfuric acid. After 8 hr chromium salts were filtered off followed by addition of 10 ml of water. The mixture was extracted twice with ether, distilled to a viscous oil, then evaporatively distilled at 40° (1 mm) to give 40 mg (67%) of β-chloroacetic acid (**22**): mp 56–57° (lit.[32] mp 57°); NMR ($CDCl_3$) δ 11.56 (s, 1 H, COOH), 4.16 ppm (s, 2 H, CH_2Cl); mass spectrum (70 eV, 40°) *m/e* (rel intensity) 96 (13, $C_2H_3{}^{37}ClO_2$), 94 (40, $C_2H_3{}^{35}ClO_2$), 51 (40), 50 (42), 49 (40), 48 (21), 45 (100), 42 (47), 34 (55).

The residue after distillation was triturated, then recrystallized from hexane to give 75 mg (68%) of the inactive form of chlorophenylacetic acid (**21**): mp 77–78° (lit.[33] mp 79°); NMR ($CDCl_3$) δ 9.84 (br, 1 H, CO_2H), 7.40 (m, 5 H, Ph), 5.36 ppm (s, 1 H, CHCl); mass spectrum (70 eV, 50°) *m/e* (rel intensity) 172 (4, $C_8H_7{}^{37}ClO_2$), 170 (13, $C_8H_7{}^{35}ClO_2$), 125 (86), 91 (100), 90 (52), 89 (36), 77 (43).

When 70 mg of a mixture of **18a** and **19a** in 3 ml of acetone were oxidized with 1 ml of 1 *M* aqueous chromium trioxide solution containing 0.05 ml of concentrated sulfuric acid for 6 hr followed by a work-up as above, a yellow oil resulted, the NMR of which showed peaks due to **21, 22,** and additional peaks at δ 8.08 (m) and 4.35 ppm (s).

Chromic Acid Oxidation of 1,3-Dichloro-4-hydroxy-4-(4′-methoxyphenyl)-2-butanone (19c). Following the procedure used for **18a** above, 160 mg of **19c** was oxidized with 2 ml of acidic 1 *M* chromium trioxide solution over 6 hr. The crude product isolated as above was crystallized from ether to give 67 mg (73%) of 4-methoxybenzoic acid (**23**): mp 184–185° (lit.[34] mp 185°); NMR ($CDCl_3$) δ 10.50 (br, 1 H, COOH), 7.98 (m, 2 H, $CH_3OC_6\mathbf{H}_4$), 6.98 (m, 2 H, $CH_3OC_6\mathbf{H}_4$), 3.68 ppm (s, 2 H, OCH_3); ir ($CHCl_3$) 3.30 (br, OH), 5.86 μ (br, C=O); parent ion in mass spectrum at *m/e* 152. The filtrate showed in addition to the acid **23** peaks, δ 4.10 ppm (s).

Irradiation of 7a. Methyl 4-Hydroxy-4-phenyl-2-butenoate (32). A solution of 500 mg (2.6 mmol) of **7a** in 150 ml of methanol was irradiated in a test tube-like apparatus under a slow stream of nitrogen with a Pyrex, 450 W Hanovia medium pressure lamp in a water-cooled, test tube-like, immersion well for 30 min. After removal of the solvent the residue was chromatographed on Florisil (activity II, 50 g). Elution with hexane–ether (4:1) afforded 330 mg (62%) of **32** as a brown liquid: NMR (CCl_4) δ 7.28 (s, 5 H, Ph), 6.92 (q, 1 H, CH=C**H**CHOH, *J* = 16 *J′* = 5 Hz), 6.00 (q, 1 H, C**H**=CHCHOH, *J* = 16 *J″* = 2 Hz), 5.15 (q, 1 H, CH=CHC**H**OH, *J′* = 5 *J″* = 2 Hz), 3.65 (s, 3 H, OCH_3), and 3.12 ppm (s, 1 H, CHO**H**); ir (neat) 2.88 (w, OH), 5.82 μ (br, C=O). Anal. Calcd for $C_{11}H_{12}O_3$: C, 68.75; H, 6.25. Found: C, 68.81; H, 6.02. A second irradiation in 150 ml of benzene with 500 mg of **7a** over 30 min gave a light yellow oil which by TLC had at least three components but which proved intractable. Attempted chromatography on silica gel, alumina, or Florisil resulted in total decomposition (see ref 2b for characterization).

Methyl 4-Oxo-4-phenyl-2-butenoate (33). A solution of 200 mg (1 mmol) of **32** in 10 ml of anhydrous ether was stirred with 400 mg of activated[35] manganese dioxide for 8 hr. Filtration and removal of the solvent gave a yellow oil which was crystallized from ether–pentane to give 148 mg (74%) of **33** as yellow crystals: mp 28.5–29.5° (lit.[17] mp 29°); NMR (CCl_4) δ 8.15–7.20 (m, Ph and one vinyl proton), 6.79 (d, 1 H, *J* = 16 Hz, vinylic), 3.75 ppm (s, 3 H, OCH_3); ir ($CHCl_3$) 5.83 (s, ester C=O), 5.99 μ (s, keto C=O).

Sensitized Irradiation of 7a. With Benzophenone. A methanol solution (50 ml), 0.0256 *M* in **7a** and 0.404 *M* in benzophenone, was divided equally into five 15-ml Pyrex test tubes. A sixth tube contained 10 ml of 0.0265 *M* solution of **7a** only. The solutions were purged with nitrogen for 15 min, sealed, and irradiated at 25° ± 3° in a Rayonet Merry-Go-Round reactor with a medium pressure Hanovia 450-W lamp through a Corning C. S. 7-83 filter to isolate the 3660-Å mercury line. Tubes were withdrawn periodically, the solvent removed, and the NMR spectrum run. After 108 hr all the **7a** in the unsensitized tube had been decomposed mainly to the ester **32** as revealed by the NMR spectrum. The NMR spectrum of a sensitized sample, after removal of excess benzophenone by crystallization from cold ether, was complex but lacked the characteristic peaks of **32.**

Attempted Sensitization with Michler's Ketone. The experiment was set up and carried out as above employing a solution $2.5 \times 10^{-3}\ M$ in Michler's ketone and $2.5 \times 10^{-2}\ M$ in **7a.** After irradiation for 96 hr the unsensitized sample was decomposed but the sensitized sample showed the NMR spectrum of only starting **7a.**

1,1-Dimethoxy-4-phenyl-3-buten-2-one (34). From 7a. A solution of 500 mg (2.6 mmol) of **7a** in 20 ml of methanol was refluxed for 48 hr.[36] Removal of the solvent gave a reddish oil which was chromatographed on alumina (activity II, 50 g). Elution with hexane–ether (7:3) afforded 440 mg (83%) of **34** as a yellow oil: bp 247–248.5° (capillary); $n^{27}\text{D}$ 1.5641; NMR (CCl$_4$) δ 7.70 (d, 1 H, J = 16 Hz, vinylic), 7.40 (m, 5 H, Ph), 6.98 (d, 1 H, J = 16 Hz, vinylic), 4.50 [s, 1 H, C**H**(OCH$_3$)], 3.38 ppm (s, 6 H, OCH$_3$); ir (neat) 6.17 μ (s, C=O). Anal. Calcd for C$_{12}$H$_{14}$O$_3$: C, 69.90; H, 6.80. Found: C, 69.67; H, 6.84.

From 36. 4-Phenyl-2-oxo-3-butenal (35). Following the procedure of Schank,[18] 11 g of **36** was treated with 8.2 g of selenium dioxide. Distillation gave 7 g (60%) of **35:** bp 140–143° (2 mm) [lit.[18] bp 120–121° (1 mm)]; NMR (CDCl$_3$) δ 9.50 (s, 1 H, HC=O), 8.02 (d, 1 H, J = 16 Hz, vinylic), 7.83–7.00 (m, 6 H, Ph and one vinylic); ir (neat) 5.82 (s, HC=O), 5.98 μ (s, keto C=O). When 1.0 g (6.2 mmol) of **35** was refluxed in 20 ml of methanol for 10 hr, followed by solvent removal and chromatography of the resultant brown oil on alumina (activity II, 50 g), the fraction eluted with hexane–ether (7:3) afforded 1.0 g (75%) of **34** with physical properties identical with those above.

Irradiation of 35. In Methanol. A solution of 390 mg (2.6 mmol) of **35** in 150 ml of methanol was irradiated (same procedure as for **7a**) for 30 min. After solvent removal, the NMR revealed a complex spectrum but lacking the characteristic peaks of **32.**

In Benzene. 35 was irradiated essentially as above but substituting benzene for methanol. The NMR of the reaction mixture was not the same as that for irradiation of **7a** in benzene.

Preparation and Thermolysis of 7a-*1-d*. To a solution of 0.10 g of **7a** in 10 ml of methylene chloride was added ca. 0.05 g of anhydrous sodium carbonate and ca. 1 ml of D$_2$O (99.5% deuterium). After stirring overnight the aqueous layer was separated and the organic phase dried with anhydrous magnesium sulfate. Two more treatments in the same way gave **7a,** mp 93–94°, containing 96.5–100% deuterium on C-1 as judged by NMR integration. This sample in a carefully dried apparatus was dissolved in 5 ml of methanol-*o-d* (99.5% deuterium). The solution was refluxed for 48 hr.[36] Removal of the solvent under reduced pressure gave a crude brown oil. The NMR spectrum of this mixture showed less than 4% of hydrogen on C-1 of **34.** Integration clearly established the 1:1 ratio of the protons on C-3 and C-4.

Registry No.—3, 28488-90-6; **5,** 56468-30-5; **6,** 20485-53-4; **7a,** 50629-66-8; **7b,** 50629-68-0; **7c,** 50629-69-1; **7d,** 50801-37-1; **7e,** 50629-70-4; **8a** isomer A, 50763-76-3; **8a** isomer B, 50629-67-9; **8d** isomer A, 56467-94-8; **8d** isomer B, 56498-04-5; **9,** 54497-04-0; **10** isomer A, 56467-95-9; **10** isomer B, 56467-96-0; **17b,** 56467-97-1; **18a,** 56467-98-2; **19a,** 56467-99-3; **19c,** 56468-00-9; **20c,** 56468-01-0; **21,** 4755-72-0; **22,** 79-11-8; **23,** 100-09-4; **32,** 55980-63-7; **33,** 14274-07-8; **34,** 55980-64-8; **35,** 6784-05-0; **36,** 122-57-6; benzaldehyde, 100-52-7; 4-nitrobenzaldehyde, 555-16-8; 4-methoxybenzaldehyde, 123-11-5; (*E*)-cinnamaldehyde, 14371-10-9; 2-thiophenecarboxaldehyde, 98-03-3; sodium hydroxide, 1310-73-2; hydrogen chloride, 7647-01-0; chromium trioxide, 1333-82-0; benzophenone, 119-61-9.

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