H), 4.40 (q, J = 7 Hz, 2 H), and 7.24 ppm (br s, 5 H). A 2,4-DNP derivative was obtained (230 mg), mp 95–96 °C, mol wt 386 (MS), identical with that obtained from the rearrangement of ethyl 2-methyl-3-phenylglycidate.

Rearrangement of Ethyl 2-Phenyl-3,3-dimethylglycidate (6t). The starting material was prepared by base-catalyzed condensation of acetone with phenylacetonitrile,[37] hydrolysis, esterification, and epoxidation with *m*-chloroperoxybenzoic acid. It showed NMR (CCl_4) at 0.97 (s, 6 H), 1.20 (t, J = 7 Hz, 3 H), 4.10 (q, J = 7 Hz, 2 H), and 7.10–7.55 ppm (m, 5 H). A solution of 100 ml of **6t** in 30 ml of benzene was treated with BF_3 for 30 min and worked up to yield 95 mg of pure **2m,** identical with the sample obtained in the rearrangement of **1m.**

Acknowledgment. Partial support of this work by the National Science Foundation and the donors of the Petroleum Research Fund, administered by the American Chemical Society, is gratefully acknowledged.

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Molecular Rearrangements with Thiol Ester Group Migration. *S*-Phenyl (*E*)- and (*Z*)-2,3-Diphenylthiolglycidates

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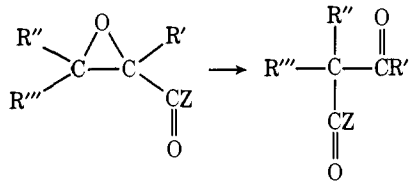
Abstract: The boron trifluoride etherate induced rearrangement of *S*-phenyl (*E*)- and (*Z*)-2,3-diphenylthiolglycidate was studied. Principally, α-phenyl migration (85%) occurs in the case of the *E* isomer (**1**). Thiol ester (35%), α-phenyl (25%), and β-phenyl (14%) migrations occur in the rearrangement of the *Z* isomer (**2**). Thiol ester migration was established by the ^{14}C labeling study described in Scheme II. Thus diastereomeric differences exist in the rearrangement of certain α,β-epoxy carbonyl systems. Mechanistic implications of this result are discussed.

Although numerous reports are available on the boron trifluoride induced rearrangement of α,β-epoxy carbonyl systems,[1-4] relatively little is known about the mechanism of these reactions. The process is of interest, since it involves migration of a carbonyl function wherein an electron-deficient carbonyl carbon moves to a positive migration terminus. The transformation of thiolglycidates to β-oxo thiol esters (Z = SR) is of particular interest, since it represents the first nonbiochemical example of migration of a thiol ester group.[3] The enzyme-catalyzed conversion of succinyl coenzyme A (CoA) to methylmalonyl CoA involving the shift of the coenzyme A thiol ester is well known.[5] In different cases, concerted as well as nonconcerted ring opening migration processes have been considered for the epoxy carbonyl rearrangement reac-

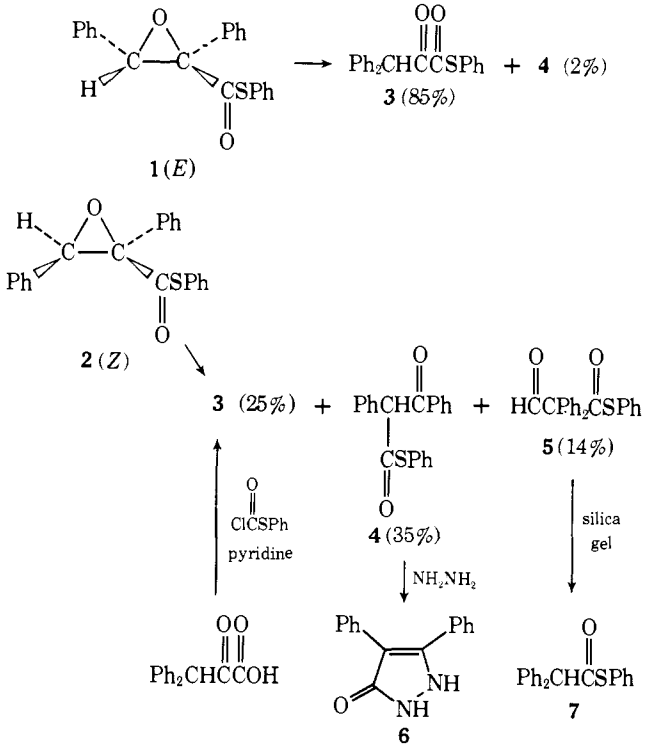


tions.[1b,c,e] However, the exact nature of the migration transition state and the structure of intermediates (if any) are still open questions.

Mechanistically, the pinacol and epoxide rearrangements are related. Recently, Kagan has found that the ester carbonyl function may serve as a migrating group in the pinacol rearrangement.[6] Stereochemical results have been used to learn about the mechanism of the pinacol rearrangement and related transformations of amino alcohols and halohydrins.[7] Studies with optically active substrates have shown that inversion and/or retention of configuration may occur at the migration terminus.[8] Other work has shown that different groups undergo migration (*arriving at the same migration terminus*), depending on whether erythro or threo diastereomers are employed.[9] This result was interpreted in terms of steric interactions in the transition state for the migration process.[10] Stereochemical specificity has also been observed in the rearrangement of *cis*- and *trans*-2,3-epoxybutanes.[11] In previous studies on α,β-epoxy carbonyl rearrangement reactions, attempts have been unsuccessful in observing diastereometric differences of this type (wherein different groups shift to the same migration terminus in the two diastereomers).[1,12] In our studies with thiolglycidates, we have now found what appears to be the first example of this phenomenon in the rearrangement of α,β-epoxy carbonyl systems, as well as the first example in a rearrangement process involving migration of a carbonyl function.

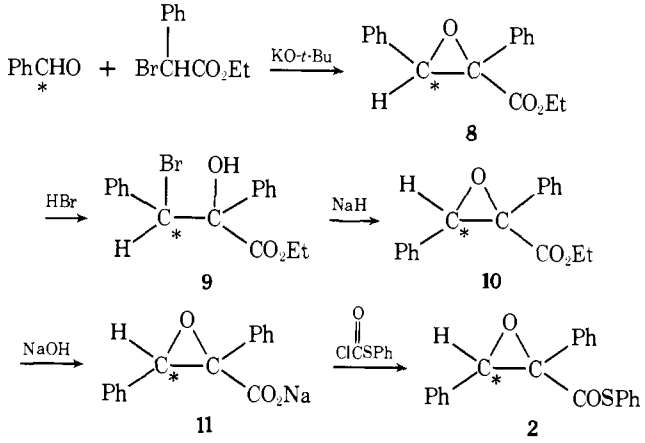
Results

Treatment of *S*-phenyl (*E*)-2,3-diphenylthiolglycidate (**1**) with boron trifluoride etherate in ether gave principally *S*-phenyl 3,3-diphenylthiolpyruvate (**3**), while similar treatment of the *Z* thiolglycidate isomer (**2**) led to substantial amounts of all three possible rearrangement products, including thiolpyruvate **3**, *S*-phenyl 2,3-diphenyl-3-oxopropanethioate (**4**), and *S*-phenyl 2,2-diphenyl-3-oxopropanethioate (**5**). The structure of **3** was established by independent synthesis. Diphenylpyruvic acid was converted to **3** with *S*-phenyl thiolchlorocarbonate and pyridine in THF solvent. β-Keto thiol ester **4** was obtained as a 1:1 mixture of keto and enol tautomers. Its structure was deduced by spectral evidence and by conversion to 3,4-diphenyl-2-pyrazolin-5-one (**6**) using hydrazine hydrate in ethanol. The aldehyde **5** has been previously prepared by BF_3-induced rearrangement of *S*-phenyl 3,3-diphenylthiolglycidate.[3b] The structure assignment for **5** was substantiated by conversion to the deformylation product, *S*-phenyl diphenylethanethioate (**7**) using sodium acetate.[3b] This deformylation reaction also occurs during attempted purification of **5** by preparative thin layer chromatography on silica gel.

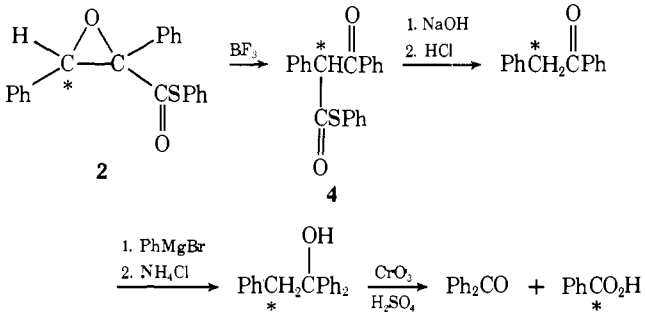


Of particular interest is the result that different amounts of **3** and **4** were isolated from the rearrangement of *trans*-(*E*)-**1** and *cis*-(*Z*)-**2** isomers of *S*-phenyl 2,3-diphenylthiolglycidate. The *E* isomer gave primarily thiolpyruvate **3** (85%), resulting from migration of the α-phenyl substituent. The NMR spectrum of the crude reaction mixture indicated a ratio 2:2:1 for products **3, 4,** and **5,** obtained from the rearrangement of *Z* isomer **2.** Thiolpyruvate **3** was isolated in 25% yield, while *S*-phenyl 2,2-diphenyl-3-oxopropanethioate (**5**) resulting from β-phenyl migration was obtained in about 14% yield. β-Keto thiol ester **4** was isolated in 35% yield. **4** may arise by either β-hydrogen or thiol ester migration. In order to resolve this question, *S*-phenyl (*Z*)-2,3-diphenylthiolglycidate-*3*-^{14}C was synthesized as shown in Scheme I, and the labeling study described in Scheme II was carried out.

Scheme I



Scheme II



Ethyl (*E*)-2,3-diphenylglycidate-*3*-^{14}C (**8**) was isomerized to the *Z* isomer (**10**) using a modification of the method of Tung and Speziale.[13] A high yield in the epoxide ring-forming

Table I. Specific Activities of Intermediates Involved in the Synthesis and Degradation of *S*-Phenyl 2,3-Diphenyl-3-oxopropanethioate (**4**)

Intermediate	Specific activity, dpm/mmol
Ethyl (*E*)-2,3-diphenylglycidate (**8**)	7.35×10^4
S-Phenyl (*Z*)-2,3-diphenylthiolglycidate (**2**)	7.43×10^4
S-Phenyl 2,3-diphenyl-3-oxopropanethioate (**4**)	7.25×10^4
Deoxybenzoin	7.35×10^4
1,1,2-Triphenylethanol	7.34×10^4
Benzophenone	0.17×10^4
Benzoic acid	6.97×10^4

step was obtained using NaH in THF in place of aqueous sodium carbonate. Sodium (*Z*)-2,3-diphenylglycidate-*3*-^{14}C (**11**) was converted to labeled **2** using *S*-phenyl thiolchlorocarbonate in THF.[14]

In the degradation (Scheme II), essentially all of the label was found in the benzoic acid, which had 95% of the specific activity present in β-keto thiol ester **4** (Table I). Thus, most of the activity in **4** is localized at position 2, suggesting that the thiol ester group has shifted in the rearrangement of **2** to **4**. Only a small amount of activity (2%) was found in the benzophenone. We can conclude that little, if any, hydrogen has migrated in this rearrangement process.

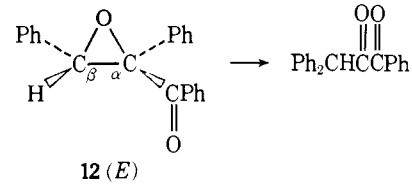
In view of the recent finding[6b] that α-keto esters may undergo rearrangement to give β-keto esters in the presence of fluorosulfonic acid, we carried out control experiments to learn about the possible interconversion of the three rearrangement products **3, 4,** and **5** under our reaction conditions. Thus, we found that thiolpyruvate **3** was not converted to either **4** or **5** under the conditions employed in the rearrangement of thiolglycidates **1** or **2,** as evidenced by examination of the NMR spectrum of the reaction mixture obtained after removal of the BF_3 catalyst by column chromatography on silica gel. Similarly, β-keto thiol ester **4** was not converted to either **3** or **5** under these same conditions. Finally, **5** was prepared as previously described[3b] and then subjected to the same test. It also was not converted to the other rearrangement products **3** and **4.**

Reexamining the product distribution obtained from *E* and *Z* isomers, we see first of all that in both cases the major ring-opening process occurs at the β position. More than 60% of the products obtained from the *Z* isomer results from an α to β shift. A major portion of this involves migration of the thiol ester function (35%). In the rearrangement of the *E* isomer, the major process (at least 85%) proceeds with migration of the α-phenyl group. Thus, we have an example of major diastereomeric differences in the products obtained in the rearrangement of *E* and *Z* isomers of an α,β-epoxy carbonyl system.

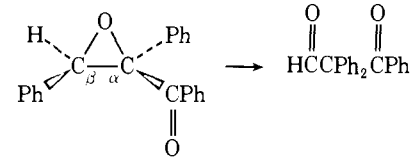
Discussion

This result may be explained by assuming that steric interactions are important in the transition state for the migration process. A steric argument of this type suggests that thiol ester (or α-phenyl) migration directly follows loss of the leaving group at the β position without formation of a carbonium ion intermediate. Alternatively, if a carbonium ion were involved, the time interval between its formation and the migration step would be shorter or approximately the same as the time necessary for a 180° rotation about the central carbon–carbon (α–β) bond.

In contrast, previous stereochemical studies on the rearrangement of α,β-epoxy ketones suggest that a carbonium ion intermediate is involved in the BF_3-induced rearrangement of α,β-epoxy carbonyl systems. Thus, a nonconcerted mechanism with a carbonium ion intermediate was proposed for the rearrangement of (*E*)- and (*Z*)-2-ethylbenzalacetophenone oxides when it was found that both isomers gave the same rearrangement product.[1c] On the other hand, the result[1b] that *E* and *Z* isomers of 2-phenylbenzalacetophenone oxide lead to different products is not, in our opinion, definite evidence for a concerted mechanism as previously suggested.[15] In fact, an explanation involving a carbonium ion intermediate is quite plausible. In this study,[1b] it was found that (*E*)-2-phenylbenzalacetophenone oxide (**12**) undergoes rearrangement with α-phenyl migration, while the *Z* isomer (**13**) gives β-phenyl



12 (*E*)

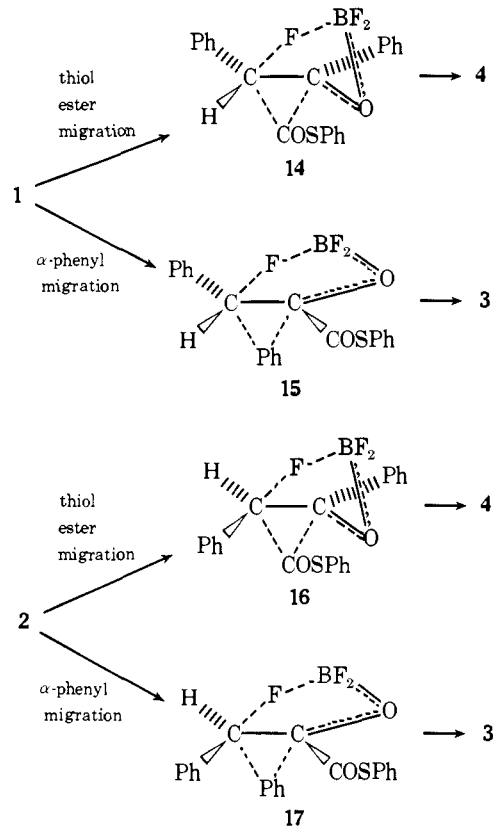


13 (*Z*)

migration. Thus, different positions serve as the migration terminus in the two isomers. At each of these positions one phenyl group is attached, which may be used to stabilize positive charge (or a long-lived carbonium ion) that develops at some point in the mechanism. In order for a phenyl group to stabilize developing positive charge in the epoxide opening step, we would expect efficient overlap of the phenyl p orbitals with the developing p orbital at the benzylic position. In the *E* isomer (**12**), steric interactions suggest that the β-phenyl group has greater opportunity to participate in orbital overlap than the α phenyl, which is *cis* to the β phenyl and also close to the benzoyl group. Thus, in the *E* isomer, positive charge (or a long lived carbonium ion) develops at the β position, resulting in α-phenyl migration. In contrast, in the *Z* isomer, the α-phenyl group has ample opportunity, sterically speaking, to stabilize developing positive charge at the α position, since it is on the opposite side of the ring with respect to both β phenyl and benzoyl groups. Steric interactions in the *Z* isomer between the β-phenyl group and the benzoyl group would tend to prevent efficient overlap of β-phenyl p orbitals with a developing p orbital at the β position. Therefore, in the *Z* isomer, positive charge (or a carbonium ion) develops at the α position and the β-phenyl substituent migrates. Thus, we feel that the stereochemical results obtained with (*E*)- and (*Z*)-2-phenylbenzalacetophenone oxides neither support nor contradict the notion that the rearrangement is concerted.

A mechanistic interpretation for our observation of diastereometric differences in the rearrangement of (*E*)- and (*Z*)-thiolglycidates **1** and **2** may be provided based on an earlier proposal of House.[1e] Mechanistic studies with α,β-epoxy ketones suggested that the migration step is concerted with departure of the leaving group at the migration terminus. Our stereochemical results with thiolglycidates provide additional support for this conclusion. However, a transition state in which epoxide ring opening is concerted with migration would involve considerable angle strain.[1e] Thus, House suggested among other proposals that the BF_3 moiety participated in an enlarged ring structure that would serve as the transition state for the migration step.

The interaction of BF_3 with (*E*)-thiolglycidate **1** may lead preferentially to α-phenyl migration via transition state **15,**



since greater steric crowding would be produced in the alternative transition state **14** involving thiol ester migration. In **14**, α- and β-phenyl substituents are positioned cis to one another. Rearrangement of the *Z* isomer **2** would occur to a considerable extent by thiol ester migration using transition state **16**. In **16**, α- and β-phenyl substituents are now situated trans to one another. However, a certain amount of α-phenyl migration would occur via transition state **17**. Steric crowding between the *S*-phenyl thiol ester and the β-phenyl group would be less severe than a corresponding cis interaction between α- and β-phenyl groups. It should also be less strained than a cis interaction between benzoyl and β-phenyl groups, which would have been encountered in the rearrangement of (*Z*)-2-phenylbenzalacetophenone oxide (**13**) if the α phenyl rather than the β phenyl shifted in this case. This last point is relevant in explaining why the major epoxide opening process in the rearrangement of (*Z*)-thiolglycidate **2** is at the β position, while ring opening occurs at the α position in the rearrangement of (*Z*)-epoxy ketone **13**.

A similar explanation based on steric interactions in the transition state may be developed for a mechanism in which epoxide opening and migration processes are concerted with one another and where the BF_3 moiety is not included in an enlarged ring structure for the transition state.

Additional support for a concerted mechanism has been obtained recently in studies on the BF_3-induced rearrangement of optically active ethyl 2-methyl-3-phenylglycidate. It has been found in this study[16] that migration of the carbethoxy group occurs with complete retention of optical purity.

Experimental Section

General. Infrared spectra were recorded on a Perkin-Elmer Model 457 spectrometer. Nuclear magnetic resonance spectra were taken on a Varian Associates Model A-60A spectrometer using tetramethylsilane (Me_4Si) as an internal standard unless otherwise stated. THF was dried over potassium–benzophenone complex and distilled prior to use. Benzene was dried over sodium metal, while ether was dried over $LiAlH_4$. Both were distilled prior to use. The petroleum ether had a boiling range of 60–110 °C. The silica gel used for column chromatography was Baker reagent grade (60–200 mesh). Silica gel GF-254 (Merck) was used for the preparative thin layer chromatography. Melting points and boiling points are uncorrected. Elemental analyses were performed by M.H.W. Laboratories, Garden City, Mich. Radioactivity measurements were carried out in a Packard Tri-Carb liquid scintillation counter (Model 3320) using toluene solvent and a PPO–POPOP scintillator system.[17]

Ethyl *erythro*-3-Bromo-2-hydroxy-2,3-diphenylpropanoate (9). Dry HBr gas was bubbled through dry benzene (500 ml) to saturate the solution. Ethyl (*E*)-2,3-diphenylglycidate (**8**)[18] (40.2 g, 0.15 mol) was added and the mixture was stirred at room temperature for 90 min before concentrating under reduced pressure to give an oily residue, which solidified on standing. Crystallization (hexane and benzene) gave pure **9** (36.6 g, 0.105 mol, 70%): mp 80–81 °C; NMR (CCl_4) δ 7.80–6.97 (m, 10 H), 5.78 (s, 1 H), 4.42 (q, J = 7.0 Hz) and 4.28 (s) (3 H), 1.37 (t, J = 7.0 Hz, 3 H); ir (KBr) 3480, 1732 cm^{-1}.

Anal. Calcd for $C_{17}H_{17}O_3Br$: C, 58.47; H, 4.91; Br, 22.88. Found: C, 58.44; H, 5.02; Br, 22.94.

Ethyl (*Z*)-2,3-Diphenylglycidate (10) (Ethyl (*Z*)-2,3-Diphenyloxiranecarboxylate). A 57% dispersion of sodium hydride in mineral oil (5.00 g, 0.12 mol) was washed with hexane (3 × 25 ml) under nitrogen and suspended in dry THF (200 ml). To this was added **9** (31.8 g, 0.091 mol) in dry THF (125 ml) over a period of 30 min at 0°. During the early part of the addition, ethanol (0.5 ml) was added to catalyze the reaction. After the addition was over, the reaction mixture was stirred at 0° for an additional 30 min and at room temperature for 1 h before filtering through a scintered glass funnel (coarse). The filtrate was added to cold water (400 ml) and ether (300 ml). The ether layer was separated and the water layer was reextracted with ether (200 ml). The combined ether layers were dried (Na_2SO_4) and concentrated to give a pale yellow oil. **10** was isolated as a colorless oil by fractional distillation (bp 165–168 °C (0.70 mm), lit.[19] 120 °C, (0.005 mm)) (19.5 g, 0.073 mol, 80%): $n^{28}D$ 1.5543 (lit.[19] $n^{25}D$ 1.5561); NMR (CCl_4) δ 7.90–7.25 (m, 10 H), 4.05 (s) and 3.98 (q, J = 7.5 Hz) (3 H), 0.92 (t, J = 7.5 Hz, 3 H); ir (thin film) 1740 cm^{-1} (broad).

Sodium (*Z*)-2,3-Diphenylglycidate (11) (Sodium (*Z*)-2,3-Diphenyloxiranecarboxylate). 10 (18.8 g, 0.070 mol) was added to a solution of sodium ethoxide in ethanol which had been prepared from sodium metal (1.66 g, 0.072 mol) and absolute ethanol (50 ml) at 0°. Water (1.8 ml, 0.10 mol) was added and the solution was stirred at 0° for 2 h. Anhydrous ether was then added and the mixture was stirred overnight. The next day filtration gave the sodium salt **11** as an amorphous powder (14.7 g, 56 mmol; 80%): mp 293–295 °C dec; NMR (D_2O, Me_4Si external standard): δ 7.50–7.10 (m, 10 H), 4.25 (s, 1 H). The NMR of sodium (*E*)-2,3-diphenylglycidate[18] is: δ 7.40–7.10 (m, 10 H), 4.60 (s, 1 H).

S-Phenyl (*E*)-2,3-diphenylthiolglycidate (1) (S-phenyl (*E*)-2,3-diphenyloxiranecarbothioate) was obtained from sodium (*E*)-2,3-diphenylglycidate[18] and *S*-phenyl thiolchlorocarbonate in THF in 63% yield using essentially the same procedure described earlier for the preparation of *S*-phenyl 1-oxaspiro [2.5]octane-2-carbothioate.[14] Recrystallization (hexane and benzene) gave pure (**1**): mp 105–107 °C; NMR (CCl_4) δ 7.30 (s) and 7.02 (s) superimposed on a multiplet between 6.95 and 7.45 (15 H), 4.45 (s, 1 H); ir (KBr) 1690 cm^{-1}.

Anal. Calcd for $C_{21}H_{16}O_2S$: C, 75.87; H, 4.85; S, 9.65. Found: C, 76.09; H, 4.99; S, 9.50.

S-Phenyl (*Z*)-2,3-diphenylthiolglycidate (2) (S-phenyl (*Z*)-2,3-diphenyloxiranecarbothioate) was obtained in a similar manner from **11** in 40% yield. Recrystallization (hexane and benzene) gave pure **2**: mp 79–81 °C; NMR (CCl_4) δ 7.80–6.80 (m, 15 H), 4.12 (s, 1 H); ir (KBr) 1690 cm^{-1}.

Anal. Calcd for $C_{21}H_{16}O_2S$: C, 75.87; H, 4.85; S, 9.65. Found: C, 75.77; H, 4.93; S, 9.37.

Rearrangement of (*E*) Isomer (1). Boron trifluoride etherate (1.66 ml, 1.3 mmol) was added to thiolglycidate **1** (1.10 g, 3.3 mmol) in ether solvent (10 ml) and the reaction was allowed to stir for 2 h at room temperature under a nitrogen atmosphere. The solution was concentrated under reduced pressure to a volume of about 3 ml before it was subjected to column chromatography on silica gel (25 g), eluting with benzene. Evaporation of the benzene eluent gave a yellow oil that crystallized on standing. The NMR spectrum of this material indicated that it was primarily *S*-phenyl 3,3-diphenyl-2-oxopropanethioate (**3**). The spectrum suggested that β-keto thiol ester **4** was also present to the extent of about 2%. Recrystallization (hexane and benzene) provided pure **3** as yellow plates (0.94 g, 85%): mp 79–81 °C; NMR (CCl_4) δ 7.27 (s) and 7.23 (s) (15 H), 5.89 (s, 1 H); ir

(KBr) 1720, 1690 cm^{-1}. The structure of **3** was established by independent synthesis.

***S*-Phenyl 3,3-Diphenyl-2-oxopropanethioate (3).** Anhydrous diphenylpyruvic acid[20] (2.28 g, 9.5 mmol) was dissolved in dry THF (25–30 ml) under a nitrogen atmosphere at 0°. Pyridine (1.20 g, 15 mmol) in dry THF (5–10 ml) and *S*-phenyl thiolchlorocarbonate (1.72 g, 10 mmol) in dry THF (5–10 ml) were added separately and simultaneously dropwise over a 30 min period. The reaction was stirred at 0° for 30 min and then at room temperature for 90 min before it was poured into cold water (200 ml) and ether (200 ml). The ether layer was separated and the water layer was reextracted with ether (100 ml). The combined ether layers were dried (Na_2SO_4) and concentrated to give an oil which was chromatographed on silica gel, eluting with petroleum ether followed by benzene–petroleum ether (1:1) to collect the product (2.3 g, 6.9 mmol, 73%). Recrystallization (hexane and benzene) gave pure **3**: mp 80–81 °C; NMR (CCl_4) δ 7.26 (s) and 7.22 (s) (15 H), 5.83 (s, 1 H); ir (KBr) 1720, 1690 cm^{-1}. The mixture melting point of this material with **3** obtained from the rearrangement reaction was not depressed.

Anal. Calcd for $C_{21}H_{16}O_2S$: C, 75.87; H, 4.85; S, 9.65. Found: C, 75.95; H, 4.69; S, 9.42.

Rearrangement of *Z* Isomer 2. Using the same rearrangement conditions described for **1, 2** was converted to a mixture of **3, 4,** and **5**. Following column chromatography on silica gel, the NMR spectrum of the resulting yellow oil suggested that **3, 4,** and **5** were present in a ratio of 41:41:18. β-Keto thiol ester **4** was present as a 1:1 mixture of keto and enol tautomers. This NMR spectrum did not suggest that other products were present in the oil. The oil was rechromatographed on silica gel, eluting with benzene–petroleum ether (1:1). There were obtained two fractions (A and B) that contained the rearrangement products. Fraction A was eluted first and consisted primarily of thiolpyruvate **3**. This was followed by fraction B, which was a mixture of **4** and **5** along with a small amount of **3**. Appreciable decomposition of thiolpyruvate **3** and aldehyde **5** occurred if these compounds were allowed to stand on the column for extended periods of time. Both fractions A and B crystallized on standing.

Fraction A was obtained as a yellow solid, which proved to be essentially pure thiolpyruvate **3** (mp 76–79 °C, 25%). Recrystallization from hexane and benzene gave pure **3** as yellow plates (mp 79–81 °C). The NMR and ir spectrum of this material were identical with those of **3** prepared using the thiolchlorocarbonate procedure described above. The mixture melting point was not depressed.

The solid from fraction B was washed with hexane. It was then recrystallized from hexane and benzene to give pure **4** as a 1:1 mixture of keto and enol tautomers (35%): mp 130–137 °C; NMR (CCl_4) δ 14.08 (s, 0.5 H), 8.0–7.1 (m, 15 H), 5.70 (s, 0.5 H); ir (KBr) 1710, 1675 cm^{-1}.

Anal. Calcd for $C_{21}H_{16}O_2S$: C, 75.87; H, 4.85; S, 9.65. Found: C, 75.72; H, 4.72; S, 9.51.

The NMR spectrum of the hexane washings of the solid obtained in fraction B indicated the presence of **3** (about 5%) along with *S*-phenyl 2,2-diphenyl-3-oxopropanethioate (**5**) (16%). Preparative thin layer chromatography on silica gel, eluting with benzene–hexane (1:1) resulted in deformylation of **5**,[3b] giving *S*-phenyl diphenylethanethioate **7** as a white solid. After recrystallization from hexane and benzene (mp 80–82 °C, 14%) **7** was obtained pure. The NMR and ir spectra of this material were identical with that of authentic **7** prepared as described previously.[3b] The mixture melting point was not depressed.

Treatment of Rearrangement Products with Boron Trifluoride Etherate. Boron trifluoride etherate (0.4 ml) was added to thiolpyruvate **3** (220 mg) in ether (2 ml) and the reaction was allowed to stir at room temperature for 2 h under a nitrogen atmosphere. The ether was removed and the residue was subjected to column chromatography on silica gel, eluting with benzene. The NMR spectrum of the resulting oil indicated the presence of only starting material **3**. Peaks associated with **4, 5,** or **7** were not detectable. In a separate experiment, β-keto thiol ester was subjected to the rearrangement conditions. Examination of the NMR spectrum after column chromatography indicated that **3, 5,** or **7** were not present. Finally, in a similar way it was found that **5** was not converted to **3** or **4** under the conditions of the rearrangement.

3,4-Diphenyl-2-pyrazolin-5-one (6). Compound **4** (166 mg, 0.50 mmol) was treated with hydrazine hydrate (0.10 g, 2.0 mmol) in ethanol (3 ml) and the solution was refluxed for 30 min and then allowed to stand overnight in the refrigerator. Evaporation of the ethanol gave a solid that was recrystallized from ethanol and water to give pure **6** as faint yellow plates: mp 232–233 °C (lit.[21] 234–235 °C).

Anal. Calcd for $C_{15}H_{12}N_2O$: C, 76.25; H, 5.12; N, 11.86. Found: C, 76.15; H, 5.22; N, 11.66.

An authentic sample of **6** was prepared from ethyl 2,3-diphenyl-3-oxopropanoate (500 mg, 1.86 mmol) and hydrazine hydrate (0.40 g, 8.0 mmol) in ethanol (5–10 ml), using acetic acid (0.5 ml) as a catalyst. The reaction mixture was refluxed for 24 h. The ethanol was removed under reduced pressure to give a solid, which was recrystallized from ethanol and water to give faint yellow plates (mp 231–232 °C). The mixture melting point of this material with the derivative prepared from **4** was not depressed.

Ethyl 2,3-diphenyl-3-oxopropanoate was prepared using the general procedure of Kimball, Jafferson, and Pike:[22] mp 86–88 °C (lit.[23] 87–88 °C); NMR (CCl_4) δ 8.13–7.83 (m, 2 H) 7.58–7.07 (m, 8 H), 5.58 (s, 1 H), 4.22 (q, 2 H, J = 7.0 Hz), 1.22 (t, 3 H, J = 7.0 Hz).

Ethyl *erythro*-3-Bromo-2-hydroxy-2,3-diphenylpropanoate-*3*-^{14}C (9). Benzaldehyde-*7*-^{14}*C*-sodium bisulfite addition complex (ICN, 0.67 mg, 23 μCi) was combined with the carrier benzaldehyde–sodium bisulfite addition complex (2.0 g, 9.5 mmol). HCl (5%) (200 ml) and ether (200 ml) were added and the mixture was allowed to stir for 2 h. The ether layer was separated and the water was reextracted with ether (4 × 100 ml). Freshly distilled carrier benzaldehyde (25.9 g, 0.24 mol) was added to the combined ether extracts and the ether was dried ($MgSO_4$) and evaporated to give the labeled benzaldehyde-*7*-^{14}C.

Ethyl 2-bromophenylacetate[24] (61.3 g, 0.25 mol) and benzaldehyde *7*-^{14}*C* (26.7 g, 0.25 mol) were dissolved in dry *tert*-butyl alcohol (200 ml) at 0° and potassium *tert*-butoxide (prepared from 9.86 g (0.25 mol) of potassium) in *tert*-butyl alcohol (400 ml) was added slowly (1 h) with stirring under a nitrogen atmosphere. The mixture was allowed to stir an additional 30 min at 0° and 2 h at room temperature. TLC analysis indicated the presence of unreacted starting materials and, therefore, additional potassium *tert*-butoxide (prepared from 1.0 g (0.025 mol) of potassium) in *tert*-butyl alcohol (40 ml) was added over a 5 min period at 0° and the reaction was then allowed to stir for 30 min at room temperature. The *tert*-butyl alcohol was removed under reduced pressure and water (300 ml) and ether (300 ml) were added. The layers were separated and the water was extracted with ether (2 × 200 ml). The combined ether extracts were dried ($MgSO_4$) and concentrated to give **8** as an oil that crystallized on standing (mp 47–53 °C). A small amount was crystallized to give pure **8** (mp 56–57 °C) (lit.[18] 59–60 °C).

The remaining crude **8** was converted to bromohydrin **9** with HBr gas, using a procedure similar to that described above for the preparation of unlabeled **9**. The product was crystallized from hexane–benzene to give a 56% yield (48.2 g, 0.14 mol, mp 78–80 °C) of labeled bromohydrin based on benzaldehyde-*7*-^{14}*C*.

***S*-Phenyl (*Z*)-2,3-Diphenylthiolglycidate-*3*-^{14}*C* (2).** The labeled bromohydrin **9** was converted to sodium (*Z*)-2,3-diphenylglycidate-*3*-^{14}*C* (**11**) using the procedure described earlier for the preparation of unlabeled **11**. Finally, labeled **2** (mp 79–81 °C) was prepared from the salt using the *S*-phenyl thiolchlorocarbonate method described previously.[14]

Rearrangement of Labeled 2. The rearrangement of the labeled *Z* isomer was carried out using the conditions described above for the rearrangement of **1**. The β-keto thiol ester **4** was purified by column chromatography on silica gel and recrystallized (benzene–hexane) to constant specific activity.

Degradation of Labeled 4. The rearrangement product **4** (475 mg, 1.4 mmol) in THF (50 ml) was added to NaOH (570 mg, 14 mmol) in water (50 ml) and the solution was stirred for 30 min under nitrogen. Concentrated HCl (5 ml) was then added and the solution was allowed to reflux for 2 h before cooling and extraction with ether (4 × 100 ml). The combined ether extracts were dried (Na_2SO_4), concentrated, and finally placed under vacuum to remove all traces of solvent and water. The resulting solid was crystallized from hexane to give deoxybenzoin (196 mg, 1.0 mmol, 71%): mp 54–55 °C. The mixture melting point with an authentic sample[25] (mp 54–55 °C) was not depressed.

Phenylmagnesium bromide was prepared from bromobenzene (296 mg, 1.9 mmol) and magnesium (46 mg, 1.9 mmol) in anhydrous ether (10 ml) under nitrogen. The labeled deoxybenzoin (185 mg, 0.94 mmol) in ether (5 ml) was added all at once to the Grignard reagent and the mixture was stirred for 15 min before it was poured into 10% ammonium chloride (50 ml). This was extracted with ether (4 × 50 ml) and the combined ether extracts were dried (Na_2SO_4), concen-

trated, and the residue was dried further overnight under reduced pressure. The resulting solid was crystallized from hexane to give pure 1,1,2-triphenylethanol (127 mg, mp 86.5–87 °C). An additional 59 mg of pure product was recovered after column chromatography of the mother liquors obtained from the above crystallization. The chromatography was carried out on silica gel, eluting with 1:1 benzene–petroleum ether. The total yield of 1,1,2-triphenylethanol was 186 mg (0.68 mmol, 72%).

Potassium dichromate (500 mg, 1.7 mmol) was added to a solution of water (3.7 ml) and concentrated sulfuric acid (1.1 ml). The labeled 1,1,2-triphenylethanol (180 mg, 0.66 mmol) was then added and the mixture was allowed to reflux for 2 h. The solution was cooled before it was poured into 10% NaOH solution (30 ml). This was extracted with ether (3 × 50 ml) and the combined ether extracts were dried (Na_2SO_4), concentrated, and the residue was dried further under vacuum. The resulting solid was dissolved in hexane and this solution was centrifuged. The filtrate was removed, concentrated, and dried under reduced pressure to give benzophenone (108 mg, mp 42–45 °C). This was crystallized from hexane to give 69 mg (57%, 0.38 mmol, mp 45–46 °C). Subsequent recrystallizations did not result in any change in the specific activity of this material.

The basic water solution remaining from the above ether extraction was acidified with concentrated HCl and extracted with ether (3 × 50 ml). The ether extracts were combined, dried (Na_2SO_4), concentrated, and the residue was dried under reduced pressure to yield benzoic acid (67 mg, mp 119–121 °C). This was crystallized from hexane to give pure material (57 mg, 0.47 mmol, 71%, mp 121–122 °C). Two additional recrystallizations resulted in only a slight increase in the specific activity of this material.[26]

The specific activities of deoxybenzoin, 1,1,2-triphenylethanol, benzophenone, and benzoic acid are recorded in Table I along with activities of the rearrangement product **4** and some of the intermediates involved in the preparation of **4**. The standard deviations obtained in the radioactivity measurements were less than 1% in all cases.

Acknowledgment. This research was supported in part by a Research Corporation Frederick Gardner Cottrell Grant. We thank Professor Robert Bach and Mr. John Domagala of Wayne State University for useful discussions.

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