

The Ionic Auxiliary Concept in Solid State Organic Photochemistry

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Received September 15, 1995

Investigations of the photochemical and photophysical behavior of organic compounds dispersed in a variety of solid environments represent a well-defined and relatively new area of research. In addition to providing basic information on the interaction of light with matter and its chemical consequences, such studies have very real applied value in the area of materials science.¹ Of the many solid environments that have been investigated—including zeolites, polymers, clays, surfaces, and others—our interests have been centered around the pure crystalline state, the major reason being that, in this medium, one has access to the very powerful technique of X-ray crystallography to pinpoint the exact structure under study. We and others have carried out extensive research that has defined the role that the molecular crystal lattice plays in controlling organic photoreactivity.² This work has shown that, compared to the results in fluid media, profound changes in reaction regio-, stereo-, and enantioselectivity can be brought about by irradiation of molecular crystals. In some cases, completely different photoproducts are formed in the solid state owing to physical restraints of the motions associated with the solution processes. In addition, through correlation of the reactivity patterns for a series of closely related compounds with their X-ray crystal structures, detailed mechanistic information on the preferred interatomic distance and angular requirements for reaction can be obtained. Schmidt and co-workers were the first to realize this in their pioneering work on the geometric requirements for [2+2] photocycloaddition reactions.³ Similarly, our

research group has been instrumental in establishing guidelines for Norrish/Yang type II hydrogen atom abstraction and related processes, data that now enable predictions to be made regarding the success or failure of such reactions for new compounds based on molecular force field calculations.⁴

Two-Component Crystalline Assemblies. With few exceptions, studies of the chemical reactivity of organic crystals have been carried out on materials consisting of one pure component. This is due to the fact that most structurally different organic compounds have very limited mutual solid state solubility, and two-component solid solutions that exist over a reasonably wide concentration range are rare. Even when some solubility does exist, the phase diagram is complex, melting point lowering occurs, and liquid phases may develop at relatively low temperatures, the result being that a true crystal lattice environment may not be present. For this reason, mixed bimolecular photochemical reactions are rare in the solid state,⁵ and techniques that are common in solution phase photochemistry, such as the use of quenchers and sensitizers, are similarly rare. For some time, therefore, it has been apparent to us that progress in the field of solid state organic photochemistry requires a reliable method of bringing together two functionally different molecular entities while still maintaining crystallinity. Our approach to this problem—that of the *ionic auxiliary*—is the subject of this Account.

The Concept of the Ionic Auxiliary. It occurred to us that one approach to overcoming the limitations described above lay in the use of *organic salts*. Salts formed between carboxylic acids and organic amines tend to be high-melting crystalline materials that offer many potential advantages for photochemical studies in the solid state. Chief among these is that they represent “natural” two-component crystalline systems in which structurally diverse organic moieties can be brought together in the solid state by means of acid–base chemistry. Through this simple expedient, the problem of mutual solid state solubility is overcome. A second property of organic salt crystals that appeals

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(1) (a) *Organic Phototransformations in Nonhomogeneous Media*; Fox, M. A., Ed.; American Chemical Society: Washington, DC, 1985. (b) Cowan, D. O.; Wiygul, F. M. *Chem. Eng. News* **1986**, July 21, p 28. (c) Fox, M. A. *Inter-Am. Photochem. Soc. Newsl.* **1993**, 16 (No. 2) p 35.

(2) For an excellent overview of the field, see: *Photochemistry in Organized and Constrained Media*; Ramamurthy, V., Ed.; VCH Publishers: New York, 1991.

(3) Schmidt, G. M. J. *Pure Appl. Chem.* **1971**, 27, 647.

(4) Scheffer, J. R. In *Organic Solid State Chemistry*; Desiraju, G. R., Ed.; Elsevier: Amsterdam, 1987; Chapter 1.

(5) For examples of mixed bimolecular photoreactions in the solid state, see: Koshima, H.; Chisaka, Y.; Wang, Y.; Yao, X.; Wang, H.; Wang, R.; Maeda, A.; Matsuura, T. *Tetrahedron* **1994**, 50, 13617 and references cited therein.

to the solid state chemist concerns their ionic character, which endows them with strong lattice forces and relatively high melting points. This suggested that they might prove to be more robust than purely molecular crystals and survive photolysis to higher conversions without loss of topochemical control, an important feature if reactions of this type are to be synthetically useful. In general, higher conversions were possible with salts, examples of which will be given later in this Account.

In the ionic auxiliary approach, the carboxylic acids and amines can be tailored through organic synthesis to serve the desired solid state function. Suppose, for example, that one wished to carry out a triplet energy transfer experiment in the crystalline state. In principle, this could be accomplished by forming a salt between a triplet energy donor containing a tethered carboxylic acid group and a triplet energy acceptor to which an amine functional group had been attached. The resulting salt would then be irradiated in the solid state and the outcome compared with that of photolyzing the probe molecule (either donor or acceptor) alone. Clearly, the opposite approach, in which the carboxylic acid component acts as the triplet energy acceptor and the amine component is the donor, is equally valid. In addition to making sensitization/quenching experiments possible in the solid state, studies of this type allow interesting correlations to be drawn between the efficacy of energy transfer and the distance between and orientation of donor and acceptor as determined by X-ray crystallography.

The role of the ionic auxiliary is by no means limited to that of acting as a sensitizer or quencher. In principle, solid state electron transfer could be studied in exactly the same way, and of course one could design the component ions so that they could react with one another in the crystalline state ([2+2] photocycloaddition, Diels–Alder reaction). The major portion of this Account will deal with yet another application of the ionic auxiliary approach, that of the *chiral* ionic auxiliary. The basic goal in this case is to bring about asymmetric induction in solid state photochemical reactions. Consider, for example, the photochemical reaction of an achiral carboxylic acid that leads to a chiral product. If we treat the carboxylic acid with an optically active amine and then photolyze the resulting salt, two diastereomeric photoproduct salts can be formed. If one of these is formed in greater amounts than the other, an asymmetric induction has been achieved and the optically active ammonium ion has acted as an ionic chiral auxiliary. As we shall see, this approach works well in the crystalline state because the *reaction medium* is chiral, which is due to the fact that optically active materials are required to crystallize in chiral space groups.

The ionic auxiliary approach also lends itself very nicely to the study of heavy atom effects in solid state organic photochemistry. Here, *inorganic* ions are the auxiliaries, and the goal of the work is to determine if and how increasing the atomic weight of the inorganic cation (e.g. Na⁺, K⁺, Rb⁺, etc.) affects the photochemical and/or photophysical behavior of an organic carboxylate anion in the solid state. Here, too, the opposite approach (Cl⁻, Br⁻, and I⁻ inorganic ions; organic ammonium ion as the probe) is likely to be equally fruitful. Finally, as an example of the practi-

cal application of the ionic auxiliary concept, we shall close this Account with a brief description of our use of these ideas in preparing crystalline materials for nonlinear optics—specifically for frequency doubling of laser light (second harmonic generation). In this approach, salts are prepared in which one ion is the chromophoric component having a large β value and the counterion is a non-absorbing species possessing a resolved stereogenic center. The latter structural feature guarantees that the salt will crystallize in the required noncentric space group.⁶

Ionic Chiral Auxiliaries. As mentioned above, the development of new methods of asymmetric synthesis in the crystalline state has been the main focus of our ionic auxiliary work; since 1990, seven papers have been published on this topic,^{7–13} and several more are in various stages of preparation. Rather than summarize each of these papers in turn, the approach to be taken in this Account will be to discuss two representative examples in somewhat more detail; the others can be read at a later date by those particularly interested in this topic.

In order to test the ionic chiral handle approach to asymmetric induction, the reactant should (1) contain an acidic or basic functional group, (2) be achiral so that salt formation with an optically active amine or carboxylic acid does not lead to diastereomers, and (3) react efficiently in the solid state to afford, after removal of the chiral handle, a product with one or more newly formed stereogenic centers. Substituted 9,10-ethenoanthracene derivatives such as **1** (Scheme 1) appeared to offer excellent prospects. Compounds of this type, while themselves achiral, undergo the well-known di- π -methane photorearrangement *via* the mechanism shown to afford chiral dibenzosemi-bullvalene derivatives of general structure **4**.¹⁴ The reaction has been well documented both in the solid state and in solution.¹⁵ All that remained, therefore, was to introduce a carboxylic acid or amine substituent into the molecule to maintain the plane of symmetry passing through C(9) and C(10). Several compounds of this type have been prepared and studied in our laboratory, but the one to be discussed in this Account is the ester–acid **5**, which was readily prepared by standard Diels–Alder reaction chemistry involving anthracene.¹¹ Treatment of compound **5** with the *tert*-butyl ester of (*S*)-proline (**6**) afforded salt

(6) Prasad, P. N.; Williams, D. J. *Introduction to Nonlinear Optical Effects in Molecules and Polymers*; Wiley-Interscience: New York, 1991.

(7) Gudmundsdottir, A. D.; Scheffer, J. R. *Tetrahedron Lett.* **1990**, *31*, 6807.

(8) Gudmundsdottir, A. D.; Scheffer, J. R. *Photochem. Photobiol.* **1991**, *54*, 535.

(9) Jones, R.; Scheffer, J. R.; Trotter, J.; Yang, J. *Tetrahedron Lett.* **1992**, *33*, 5481.

(10) Gudmundsdottir, A. D.; Li, W.; Scheffer, J. R.; Rettig, S.; Trotter, J. *Mol. Cryst. Liq. Cryst.* **1994**, *240*, 81.

(11) Gudmundsdottir, A. D.; Scheffer, J. R.; Trotter, J. *Tetrahedron Lett.* **1994**, *35*, 1397.

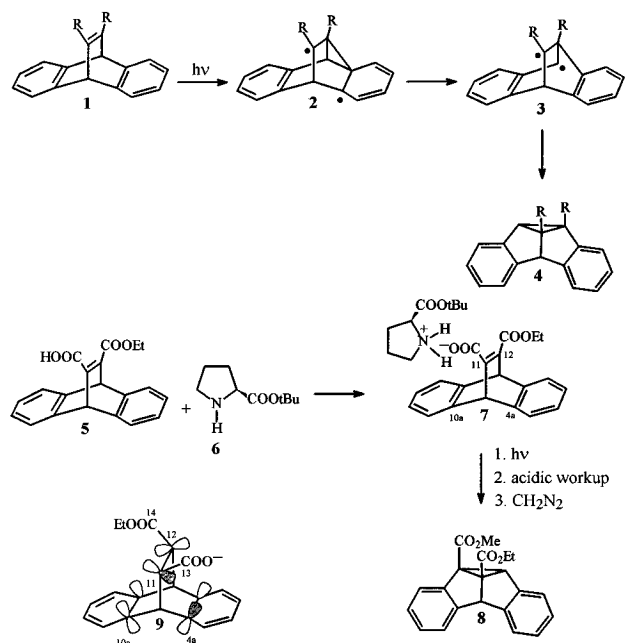
(12) Jones, R.; Scheffer, J. R.; Trotter, J.; Yang, J. *Acta Crystallogr.* **1994**, *B50*, 601.

(13) Koshima, H.; Maeda, A.; Masuda, N.; Matsuura, T.; Hirotsu, K.; Okada, K.; Mizutani, H.; Ito, Y.; Fu, T. Y.; Scheffer, J. R.; Trotter, J. *Tetrahedron: Asymmetry* **1994**, *5*, 1415.

(14) For a recent general review of the di- π -methane rearrangement, see: Zimmerman, H. E. In *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1991; Vol. 11, Chapter 1.

(15) For recent reviews on the photochemistry of 9,10-dihydro-9,10-ethenoanthracene and its derivatives, see: (a) Chen, J.; Scheffer, J. R.; Trotter, J. *Tetrahedron* **1992**, *48*, 3251. (b) Scheffer, J. R.; Trotter, J.; Gudmundsdottir, A. D. In *CRC Handbook of Organic Photochemistry and Photobiology*; Horspool, W. M., Song, P.-S., Eds.; CRC Press: Boca Raton, FL, 1995; Chapter 50.

Scheme 1



7, and irradiation of crystals of this salt gave diester **8** following acidic workup to remove the ionic chiral auxiliary and treatment with diazomethane to transform the resulting carboxylic acid into its methyl ester. With nonequivalent substituents on the bridging double bond, salt **7** can in principle lead to two photoproducts—compound **8** and its regioisomer in which the methyl and ethyl ester substituents are interchanged. In the event, however, regioisomer **8** was formed exclusively in the solid state for reasons that we do not fully understand, since both regioisomers were formed in approximately equal amounts in solution.

The enantioselectivity of the solid state photoreaction of salt **7** was established by 400 MHz chiral shift reagent NMR using $\text{Eu}(\text{hfc})_3$. This showed that photoproduct **8** was formed in over 95% enantiomeric excess at 20% conversion. Similar high enantiomeric excesses have been observed in several other instances during the course of our ionic chiral auxiliary work, but such excellent results have by no means been obtained for every salt investigated. We shall address this point in more detail later in this Account. Concomitant with the photochemical studies, the X-ray crystal structure of salt **7** was determined. Because the absolute configuration of the prolinium ion component of the salt is known, the crystal structure of the salt gives us the absolute configuration of the anionic component, which is chiral owing to its fixed disymmetric conformation in the crystalline state. This disymmetry arises because of twisting about the bridging C(11)–C(12) double bond, and the absolute sense of this twist as well as its magnitude is given by the value of the C(13)–C(11)–C(12)–C(14) torsion angle, which is -9° . A drawing emphasizing this torsion angle is given by structure **9** in Scheme 1.

The absolute configuration of photoproduct **8** was also determined, in this case by converting it into the corresponding diisopropyl diester, whose absolute configuration had been established by us some time

ago by X-ray crystallography.¹⁶ This set the stage for a very pretty experiment involving a correlation of the absolute configuration of salt **7** with that of its photoproduct **8**. This showed that crystals of salt **7** that had a -9° torsion angle gave diester **8** with the absolute configuration shown in Scheme 1, and this allowed us to conclude that initial benzo–vinyl bridging occurs between C(11) and C(4a), since the only other bonding pathway that leads to **8**, (C(11)–C(10a) bridging) gives the wrong enantiomer. To what can we ascribe the preference for C(11)–C(4a) over C(11)–C(10a) bridging in the solid state? While it is possible that intermolecular crystal lattice forces have some effect on enantioselectivity, as they apparently do on regioselectivity, such interactions are not obvious from inspection of the packing diagrams, and we attribute the enantioselectivity mainly to an intramolecular steric effect in which the vinyl substituents seek to remain as far from one another as possible during the benzo–vinyl bridging process. Inspection of structure **9** (Scheme 1) clearly reveals that the interaction between the vinyl substituents should be *reduced* during C(11)–C(4a) bridging rather than increased as it would be if C(11)–C(10a) bridging were followed; adherence to the latter pathway would necessarily involve eclipsing at some stage. A second factor that favors the observed enantioselectivity is orbital overlap. Owing to the negative torsion angle in salt **7**, the p-orbital at C(11) overlaps better with the p-orbital at C(4a) than with the p-orbital at C(10a), thus reinforcing the preference for the former pathway. Lending credence to these ideas is the fact that exactly analogous orbital overlap and intramolecular steric effect arguments successfully rationalize the absolute steric courses of three other solid state di- π -methane photorearrangements of ethenoanthracenes, one of a salt¹¹ and two that are nonionic in nature.^{16,17}

A final important point concerns the enantioselectivity of the fluid phase photorearrangement. Irradiation of salt **7** in acetone led to both di- π -methane regioisomers, and neither showed any trace of optical activity. Similar results have been obtained for all ionic chiral auxiliary salts investigated. Evidently, in solution, the ions are not sufficiently well oriented or closely associated to lead to significantly different diastereomeric transition state free energies.

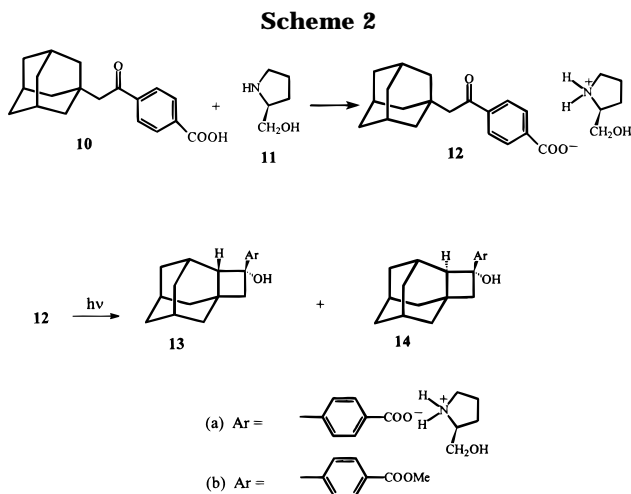
We turn now to a second salt whose photochemistry we have investigated from the ionic chiral auxiliary point of view—the adamantylacetophenone derivative **12** shown in Scheme 2.^{9,12} This substance was prepared by the reaction of carboxylic acid **10** with L-prolinol (**11**), and photolysis of this material in the crystalline state led to the Norrish/Yang type II cyclobutanols **13** and **14** in a ratio of approximately 5.5:1. Type II cleavage is disfavored in this case since it would lead to the highly strained adamantene.¹⁸ Compound **10** fulfills the requirements outlined earlier for ionic chiral auxiliary studies; namely, it is an acidic, achiral substance (**10**) that reacts photochemically to give chiral products.

The choice of salt **12** provided an unexpected and welcome bonus: it proved to be dimorphic. Recrys-

(17) Fu, T. Y.; Liu, Z.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1993**, *115*, 12,202.

(18) For a review of the Norrish/Yang type II reaction, including a discussion of the factors that influence the cyclization to cleavage ratio, see: Wagner, P.; Park, B.-S. In *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1991; Vol. 11; Chapter 4.

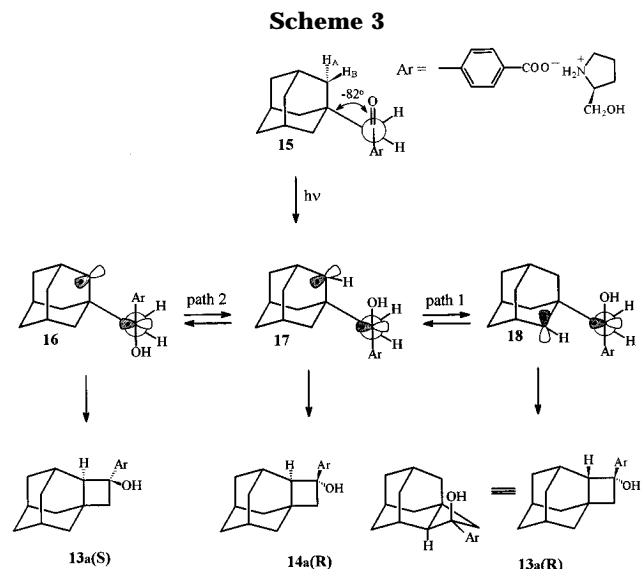
(16) Garcia-Garibay, M.; Scheffer, J. R.; Trotter, J.; Wireko, F. *J. Am. Chem. Soc.* **1989**, *111*, 4985.



tallization from acetone produced an initial crop of platelike crystals, mp 116–118 °C, whereas needle-shaped crystals, mp 128–130 °C were obtained from the mother liquor. The X-ray crystal and molecular structure of each dimorph was obtained by direct methods. The phenomenon of dimorphism (and polymorphism in general) is welcomed by solid state chemists, as it gives them the opportunity to investigate the chemical behavior of the same substance in two or more solid state environments and thereby learn more about the role of crystal lattice forces in governing reactivity. In this regard, salt **12** did not disappoint us. Photolysis of the needle dimorph of this material followed by acidification and diazomethane workup gave cyclobutanol derivative **13b** in 97% enantiomeric excess (ee) (dextrorotatory enantiomer favored), and identical treatment of the plate dimorph led to the same product, but in only 12% ee and with the levorotatory enantiomer predominating. This result was obtained at conversions lower than those used for the needle dimorph, which suggests that crystal breakdown in the later stages of reaction is not the major factor responsible.

The X-ray crystal structures of the dimorphs reveal the likely reason for the different enantioselectivities: the carboxylate anions in the needle crystals adopt a single, homochiral conformation, whereas in the plate form, there are equal numbers of two crystallographically independent carboxylate anions in the asymmetric unit that have *opposite absolute configurations*, even though each is associated with an (*S*)-(+)-prolinol-derived cation. Given this information, the most straightforward explanation of the results is that the molecules from which the needle crystals are composed react stereospecifically from a single conformational stereoisomer to give a single stereoisomer of the photoproduct. In the plate crystals, however, there are *competing* stereospecific photoreactions, and these result in a product of low overall enantiomeric excess. Because the reaction is occurring in a chiral environment, the competing reactions have diastereomeric transition states of unequal energy, thus accounting for the nonracemic nature of the photoproduct.

As part of this project, we were anxious to determine the absolute configuration of photoproduct **13** so that we could carry out an absolute-to-absolute configuration correlation study of the type described earlier for the ethenoanthracene system—a type of study that



represents one of the most powerful methods in existence for investigating crystal structure–reactivity relationships. By good fortune, crystallization of the photolysis mixture from acetone led to deposition of crystals that contained not only salt **13a** but unreacted starting salt **12** as well, and a crystal structure of this complex was successfully determined.¹² Since the absolute configuration of prolinol is known, this crystal structure, plus that of the needle dimorph of salt **12** alone, gives us the desired absolute configuration correlation. The results show that a crystal of the needle dimorph of salt **12** in which the absolute sign of the O=C–C(α)–C(β) dihedral angle is negative leads to photoproduct **13a** in which the absolute configuration at the hydroxyl-bearing carbon atom is *R*.

The structural relationships are shown in Scheme 3. Structure **15** depicts the reactant in which the dihedral angle that defines the absolute configuration is -82° . The analysis requires that we know which γ -hydrogen is abstracted, and this is without doubt H_B , which lies at a distance of 2.70 Å from the carbonyl oxygen and is only 46° out of the carbonyl plane. Hydrogen atom abstractions involving similar geometries have been well documented.^{4,18} Abstraction of H_B leads to biradical **17**, which we assume has the same basic conformation as its precursor **15** in the restrictive solid state medium. At this point, an unexpected thing happens. Direct, least motion closure of biradical **17** through overlap of the shaded orbitals leading to photoproduct **14a**, a process that should be favored topochemically in the solid state, occurs only about 15% of the time,¹⁹ probably because of unfavorable steric interactions that are developed between the adamantane ring and the aryl group. Instead, photoproduct **13a** is formed, and this can happen in two ways: (1) by rotation of biradical **17** about the C(α)–C(β) bond to give biradical **18**, which undergoes closure to the *R* form of **13a**, or (2) by rotation about the C(α)–C(OH)Ph bond to form biradical **16**, which then closes to the *S* enantiomer of **13a**. The absolute configuration correlation results

(19) Although photoproduct **14a** is shown as having the *R* absolute configuration at the hydroxyl-bearing carbon, lack of material prevented us from obtaining its absolute configuration or even the enantiomeric excess in which it is formed.

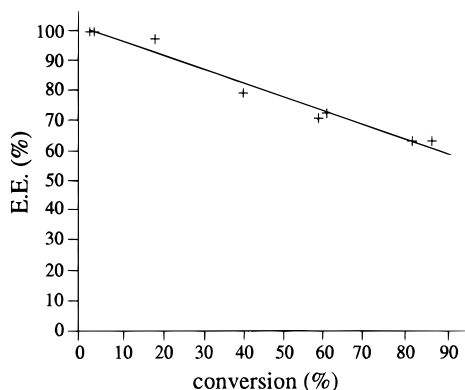


Figure 1. Typical enantiomeric excess vs conversion plot for a solid state photorearrangement employing an ionic chiral auxiliary.²¹

indicate that pathway 1 is followed, and this makes sense because it should clearly be easier for the spherical adamantane moiety to rotate about an axis in the solid state than for the aryl and hydroxyl groups to exchange positions, a process that would disrupt the strong ionic and hydrogen bond forces between the carboxylate anion and the prolinol cation.²⁰

A small amount of the topochemically disfavored *S* enantiomer of photoproduct **13a** is, nevertheless, formed in these experiments, and the question is how does this happen? The traditional explanation for nontopochemical solid state behavior is that it takes place at one or more of the following sites: the surface, preexisting defect sites, or defect sites generated by reaction. All three sites share the common feature that the high degree of order characteristic of the perfect crystal lattice is absent, thus allowing reactions to occur that would normally be topochemically forbidden. If defects generated by reaction contribute to nontopochemical behavior, then the extent of nontopochemical behavior should increase with increasing conversion. Exactly such behavior has been found in one of our unpublished ionic chiral auxiliary studies, and Figure 1 shows a plot of enantiomeric excess versus percent conversion obtained in this case.²¹

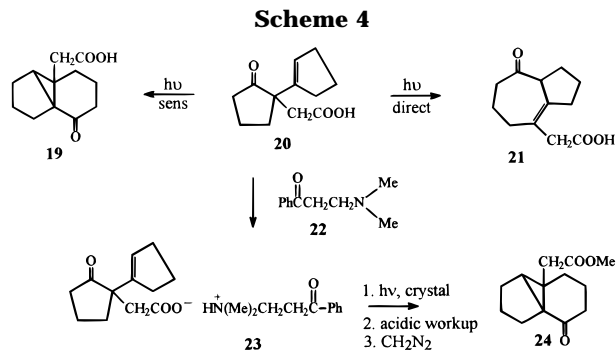
From Figure 1 it can be seen that enantiomeric excesses of 60–70% can be obtained even at conversions approaching 100%. Still higher conversions can be tolerated without undue loss of enantioselectivity in the case of salt **12**. Here, the reported 97% enantiomeric excess was obtained at a conversion of 87%.⁹ In comparison, the enantioselectivity obtained from photolysis of purely molecular crystals tends to fall off seriously at a much earlier stage.²² This is not always the case, however. Sekine *et al.* have reported the photolysis of a molecular crystal that affords a product with an enantiomeric excess of 93% at 75% conversion.²³

(20) Rotations of globular substituents about single bonds have been well documented in the crystalline state. See: (a) Gavezzotti, A.; Simonetta, M. In *Organic Solid State Chemistry*; Desiraju, G., Ed.; Elsevier: Amsterdam, 1987; Studies in Organic Chemistry, Vol. 32, Chapter 11, pp 391–432. (b) Riddell, F. G.; Bernáth, G.; Fülöp, F. *J. Am. Chem. Soc.* **1995**, *117*, 2327.

(21) The plot of Figure 1 is for the solid state photolysis of the salt formed between (+)-pseudoephedrine and *cis*-4-*tert*-butyl-1-methylcyclohexyl phenyl ketone. The data were obtained from the following reference: Leibovitch, M.; Olovsson, G.; Sundarababu, G.; Ramamurthy, V.; Scheffer, J. R.; Trotter, J. *J. Am. Chem. Soc.* **1996**, *118*, 1219.

(22) Caswell, L.; Garcia-Garibay, M. A.; Scheffer, J. R.; Trotter, J. *J. Chem. Educ.* **1993**, *70*, 785.

(23) Sekine, A.; Hori, K.; Ohashi, Y.; Yagi, M.; Toda, F. *J. Am. Chem. Soc.* **1989**, *111*, 697.



Ionic Sensitizers and Ionic Heavy Atom Effects. For compounds in which intersystem crossing is slow following direct irradiation, population of the triplet excited state requires either the use of triplet energy sensitizers or the introduction of heavy atoms to decrease the forbiddensness of the singlet–triplet transition (heavy atom effect).²⁴ Because sensitization techniques have been difficult in the crystalline state until now, the triplet state photochemistry of such compounds has not been studied in this medium. β,γ -Unsaturated ketones represent a photochemically important class of compounds that fall into this category. Upon direct irradiation, the majority of β,γ -unsaturated ketones undergo a singlet-mediated 1,3-acyl shift (1,3-AS) reaction to produce a rearranged β,γ -unsaturated ketone. Triplet-sensitized photolysis of these compounds, on the other hand, leads to the well-known and synthetically useful oxadi- π -methane (ODPM) rearrangement.²⁵ Motivated by a desire to study this latter photorearrangement in the solid state in order to establish detailed structure–reactivity relationships, we selected the carboxylic acid-containing β,γ -unsaturated ketone derivative **20** (Scheme 4) for our initial investigations. Previous work by Coffin *et al.* had shown that this compound undergoes primarily a 1,3-AS reaction in solution to give compound **21**, and that sensitized photolysis of this material affords mainly the ODPM-derived cyclopropyl ketone **19**.²⁶

Our first task was to determine whether β,γ -unsaturated ketone **20** shows the same characteristic 1,3-AS reactivity upon direct irradiation in the crystalline state as in solution. It does, and the stage was now set for the introduction of an ionic sensitizer through salt formation of keto-acid **20** with an appropriate amine. The amine chosen was (dimethylamino)propiofenone (**22**), which is commercially available from Aldrich as its hydrochloride salt. Reaction of keto-amine **22** with keto-acid **20** afforded salt **23** as a white powder, and irradiation of this material in the solid state at wavelengths where only the aryl ketone absorbs ($\lambda > 330$ nm) led to ODPM ester **24** as the sole isolable product following acidic workup and treatment with diazomethane.²⁷ Only traces of ODPM product **24** could be detected as a result of photolyzing salt **23** in ethanol at the same wavelengths. Evidently the solution was too dilute (10^{-2} M) for much energy

(24) For a review of the heavy atom effect in organic photochemistry, see: Kozlar, J. C.; Cowan, D. O. *Acc. Chem. Res.* **1978**, *11*, 334.

(25) For a recent review of the photochemistry of β,γ -unsaturated ketones, see: Demuth, M. In *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1991; Vol. 11, Chapter 2.

(26) Coffin, R. L.; Cox, W. W.; Carlson, R. G.; Givens, R. S. *J. Am. Chem. Soc.* **1979**, *101*, 3261.

(27) Gamlin, J. N.; Scheffer, J. R. Unpublished results.

Table 1. Photolysis of Keto-Acid **20 and Its Salts in Various Media^a**

compound photolyzed	21:19 (solution)	21:19 (crystal)
carboxylic acid	85:15 (hexane)	95:5
carboxylic acid	5:95 (acetone)	95:5
Li ⁺ salt	>99:1 (water)	90:10
Na ⁺ salt	>99:1 (water)	48:52
K ⁺ salt	>99:1 (water)	35:65
Rb ⁺ salt	>99:1 (water)	40:60
Cs ⁺ salt	>99:1 (water)	60:40

^a The product ratios were determined by capillary gas chromatography following acidification and diazomethane workup to form the methyl esters of photoproducts **19** and **21**. The solid state K⁺ and Rb⁺ ratios are probably not significantly different from one another within experimental error.

transfer to occur during the excited state lifetime of the sensitizer. Similar solid state and solution phase results were obtained when *p*-acetyl-*N,N*-dimethylbenzylamine was used in place of (dimethylamino)-propiophenone.

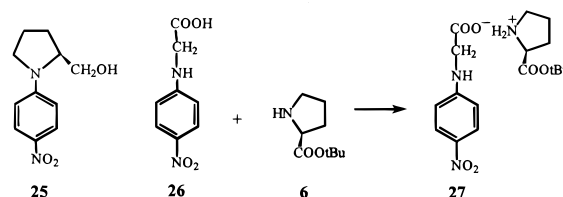
Having demonstrated the feasibility of employing ionic sensitizers to bring about triplet state reactions in the solid state, we next turned our attention to promoting triplet state reactivity in crystals through an ionic heavy atom effect. The idea here was that by forming salts of keto-acid **20** with increasingly heavy metal hydroxides, it might be possible to observe a heavy atom effect on the 1,3-AS/ODPM product ratio in the solid state. At the outset, this seemed like an unlikely prospect, as previous attempts to observe both internal²⁸ and external²⁹ heavy atom effects on the photochemistry of β,γ -unsaturated ketones in solution had found no evidence for enhanced ODPM behavior upon direct photolysis.

The Li⁺, Na⁺, K⁺, Rb⁺, and Cs⁺ salts of keto-acid **20** were prepared, recrystallized, and subjected to direct irradiation in the solid state as well as in solution.³⁰ The results are summarized in Table 1. As can be seen, there is a strong cation effect in the crystalline state but none in solution. The latter result is not surprising given the failure of the other ionic auxiliaries discussed in this Account to exert their effect in solution. The results compiled in Table 1 are intriguing in that, contrary to expectation,²⁴ the greatest perturbation of the photoproduct ratio does not come from the salt with the heaviest metal ion. This distinction belongs to the relatively light potassium ion, and the even lighter sodium ion exerts an effect that is greater than that of the much heavier cesium cation. One factor that undoubtedly contributes to these unexpected results is that the salts have different crystal structures with different distances between and orientations of the metal ions and the organic moieties. This is borne out in the crystal structures of the K⁺ and Rb⁺ salts of keto-acid **20**. For example, in the case of the potassium salt, the closest contact between the oxygen atom of a ketone group and a K⁺ ion is 2.79 Å, whereas in the rubidium salt, the shortest C=O...Rb⁺ distance is 3.43 Å. The difference in these contacts is much larger than the difference in the ionic radii of K⁺ (1.33 Å) and Rb⁺ (1.48 Å).

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(29) Schuster, D. I.; Calcaterra, L. T. *J. Am. Chem. Soc.* **1982**, *104*, 6397.

(30) Borecka, B.; Gudmundsdottir, A. D.; Olovsson, G.; Ramamurthy, V.; Scheffer, J.R.; Trotter, J. *J. Am. Chem. Soc.* **1994**, *116*, 10,322.

Scheme 5

Nevertheless, we suspect that, in addition to their heavy atom effect, the metal ions may be affecting the photoproduct ratios through their coordination to the β,γ -unsaturated ketone oxygen atoms. One indication that this might be so comes from the work of Ramamurthy *et al.*, who showed that, for macrocyclic ketones that can undergo both the Norrish type I and type II reactions, the proportion of type I behavior is markedly increased when the photolyses are carried out in the cavities of alkali-metal-containing zeolites.³¹ Here, too, especially large enhancements were obtained for Li⁺ and Na⁺, which are expected to bind more strongly to the carbonyl chromophore. The exact mechanism by which the cations alter the photoproduct ratios is, however, not well understood at the present time. Recent, unpublished work from our laboratory indicates that Li⁺ and Na⁺ also strongly perturb the ratio of singlet-derived to triplet-derived products obtained in the solid state photolysis of certain nonketonic 9,10-ethenoanthracene derivatives.²⁷

Ionic Auxiliaries for Second Harmonic Generation. We close this Account with a very brief description of our unpublished work on the application of the ionic auxiliary concept to the preparation of new materials for nonlinear optics. Only one example is presented, which we hope will be sufficient to give the reader an appreciation of the approach taken; a paper that provides a more thorough account of this work is currently in preparation.³²

p-Nitroaniline is the quintessential nonlinear optical (NLO) chromophore, and several of its derivatives have been explored for potential use in the frequency doubling of laser light and other NLO applications.³³ In order to observe a second-order nonlinear optical effect in crystals, the material must pack in a noncentric space group, and Zyss *et al.* accomplished this for the *p*-nitroaniline chromophore by introducing a resolved stereogenic center into the nitrogen-containing *p*-substituent, e.g., NPP (**25**, Scheme 5).³⁴ On the basis of our solid state asymmetric induction work discussed earlier, we reasoned that an ionic chiral auxiliary approach could be used to generate *salts* that would have second-order NLO properties. The basic idea was the following: prepare a nonchiral *p*-nitroaniline derivative that contains a tethered carboxylic acid functional group and react this with an optically active amine. The resulting salt is expected to be a robust, high-melting-point crystalline solid which, because of the optical activity of the ionic auxiliary, must pack in a noncentric space group.

(31) Ramamurthy, V.; Lei, X.-G.; Turro, N. J.; Lewis, T. J.; Scheffer, J. R. *Tetrahedron Lett.* **1991**, *32*, 7675.

(32) Bree, A.; Patrick, B.; Scheffer, J. R.; Trotter, J. Unpublished results.

(33) Eaton, D. F. In *Materials for Nonlinear Optics: Chemical Perspectives*; Marder, S. R., Sohn, J. E., Stucky, G. D., Eds.; American Chemical Society: Washington, DC, 1991; Chapter 8.

(34) Zyss, J.; Nicoud, J. F.; Coquillay, M. *J. Chem. Phys.* **1984**, *81*, 4160.

Scheme 5 shows an example of this approach. *N*-(*p*-Nitrophenyl)glycine (**26**), which is readily available from glycine methyl ester and *p*-nitrofluorobenzene, reacts with the *tert*-butyl ester of proline (**6**) to afford salt **27**. Crystals of this salt are nonlinearly active, showing a second harmonic generation (SHG) efficiency approximately 15 times that of urea at 1064 nm by the Kurtz and Perry powder method.³⁵ For comparison purposes, NPP exhibits a SHG efficiency *ca.* 60 times that of urea at the same wavelength. In addition to numerous analogs of salt **27**, we have prepared quite a number of salts in which the amine component contains the NLO chromophore and the acid component serves as the ionic chiral auxiliary. Current work in our group is aimed at improving the SHG response by extending this approach to carboxylic acid- and amine-containing NLO chromophores having larger β values.³⁶

Summary and Concluding Remarks. The ionic auxiliary concept has been shown to be useful for bringing together two dissimilar chemical entities in the solid state for the purposes of (1) asymmetric induction in solid state photochemical reactions, (2) triplet energy sensitization of a solid state photoreaction, (3) the introduction of metal ions for studies of the heavy atom effect in solid state organic photochemistry, and (4) the preparation of new crystalline materials having potentially useful second-order nonlinear optical properties. Other applications, for example, the generation of charge separation in the crystalline state through photoinduced electron transfer between a donor anion and an acceptor cation (or *vice versa*), are still on the drawing board, and we hope

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(36) For a similar study, see Marder, S. R.; Perry, J. W.; Yakymyshyn, C. P. *Chem. Mater.* **1994**, *6*, 1137.

(37) (a) Ito, Y.; Borecka, B.; Trotter, J.; Scheffer, J. R. *Tetrahedron Lett.* **1995**, *36*, 6083. (b) Ito, Y.; Borecka, B.; Olovsson, G.; Trotter, J.; Scheffer, J. R. *Tetrahedron Lett.* **1995**, *36*, 6087.

that additional uses of ionic auxiliaries will emerge as a result of this Account.

One interesting extension of the basic ionic auxiliary concept that we can mention in closing is that due to Ito *et al.* in which diamines are used to form double salts with α,β -unsaturated carboxylic acids. In some of these materials, the crystal packing is such that the double bonds of neighboring carboxylate anions are aligned properly for [2+2] photocycloaddition, and irradiation of the salt crystals leads to dimers that have different stereo- and regiochemistry compared to the photodimers formed by solid state photolysis of the carboxylic acids alone.³⁷

In comparison to purely molecular (nonionic) crystals, salts offer a number of advantages for investigating chemical phenomena in the solid state. They are easy to prepare, are highly crystalline, have strong lattice forces and high melting points, can be reacted to relatively high conversions without loss of topological control, and offer an inexpensive and reliable way of generating chiral space groups for nonlinear optical and asymmetric induction studies, and after use, the ionic auxiliaries can be removed easily by simple acid–base chemistry. Studies of the solid state photochemical behavior of organic salts add a new dimension to the burgeoning field of supramolecular photochemistry—the use of multicomponent organized assemblies for the purpose of modifying and controlling photochemical reactivity. We are continuing our investigations in this fascinating field and encourage others to do so as well.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research. Financial support by the Natural Sciences and Engineering Research Council of Canada is also gratefully acknowledged.

AR950165Q