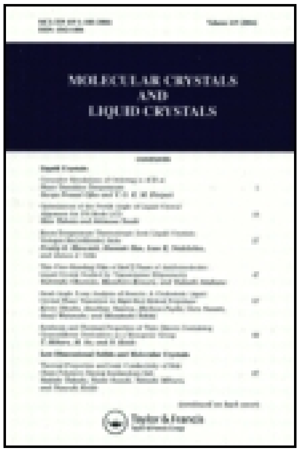

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Isotopic Mixing in OO′-Dideuterosuccinic Acid Single Crystals

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Abstract—Extensive isotopic mixing in partially deuterated succinic acid single crystals brought about by moderate doses of ionizing radiation point to a radiochemical reaction occurring with very large G value and thus to a free radical chain reaction. The isotopic mixing is evident in the ESR spectrum of the free radicals produced in low concentration and also, remarkably, in the IR absorption spectrum which reveals that a considerable fraction of all of the molecules in the crystal are involved. The evidence points to the possibility that hydrogen atom vacancies in organic crystals may sometimes be mobile, and so constitute a unique type of crystal defect.

Introduction

To aid in the interpretation of the ESR spectra of free radicals in irradiated organic crystals a frequent recourse is to compare the spectra with those of isotopically substituted analogues,[1,2] most commonly using the partially deuterium substituted crystal which is obtained by recrystallizing the compound from heavy water solution. This procedure is based on the assumption that irradiating the isotopically substituted crystal will produce free radicals which are structurally the same as in the normal crystal and that if changing some of the protons to deuterons produces no change in the spectra (other than a slight reduction of the inhomogeneous broadening) one can conclude that the electron spin is not coupled with any of the exchanged hydrogens. The picture of free radical production that is implied by this assumption is that the ionizing radiation merely provides sufficient energy to break the covalent bonds of the molecule and knocks off pieces of it to leave free radicals with " dangling " bonds. A warning that this simple bond-breaking hypothesis will not always suffice was given in a paper by Pooley and Whiffen[3] who reported their examination of the ESR spectrum of irradiated OO′-dideuterosuccinic acid which they had prepared in connection with the interpretation of the ESR spectra of the radical $HOOCCH_2\dot{C}HCOOH$ in normal succinic acid crystals. The expected radical, $DOOCCH_2\dot{C}HCOOD$, was indeed formed and showed essentially the same spectrum as its hydrogen analogue. Unexpectedly the spectrum contained additional lines attributable to the radical $DOOCCHD\dot{C}HCOOD$ or its O-hydrogen analogues. The deuterium on the carbon backbone appears to have arrived there by exchange between the polar deuterium atoms and the aliphatic hydrogen atoms. This sort of phenomenon, since observed in crystals of other compounds has come to be called " isotopic mixing " [4,5].

The case described above clearly calls for an interpretation that goes beyond the naive concepts of the simple bond breaking hypothesis. Pooley and Whiffen[3] advanced a specific suggestion as to how the isotopic exchange may occur, namely that " the radical might be formed by attack by D or D^+ when the incoming particle might be confined to certain geometrical paths by virtue of the crystal structure ". In essence this hypothesis would explain the stereospecific nature of the exchange by invoking the fact that a chemical reaction in a molecular solid is topochemically determined. It is the purpose of this paper to put forward a rather general mechanism by which isotopic mixing can take place. Known examples of isotopic mixing are discussed in the light of this hypothesis and new experimental evidence brought forward in support of it.

Free Radical Isomeric Transformations

Our starting point is to notice that the conversion of a molecule into a free radical by the removal of a hydrogen atom is equivalent to the introduction of a sort of vacancy. This vacancy can in principle receive a hydrogen atom from another site on the molecule with the transfer of the vacancy to that site. This process is familiar as an isomeric transformation. It results in the transfer of hydrogen atoms, a process which is not possible without the presence of the vacancy which promotes the " shuffling " of the hydrogen atoms among those sites which the hole can visit, in essentially the same way as the presence of vacancies in a crystal lattice promotes the mobility of atoms in the crystal. Let us for example consider a hypothetical but not unrealistic case, viz. the molecule CH_3CD_3, a partially deuterated ethane. If a C_2 free radical were to be made by irradiating this compound, then the predictions of the simple bond-breaking theory lead us to expect only the radicals $\dot{C}H_2CD_3$ and $CH_3\dot{C}D_2$. However, it is easily seen that a sequence of isomeric transformations will yield the species $\dot{C}HDCHD_2$, $\dot{C}D_2CH_2D$, $\dot{C}HDCH_2D$ and $\dot{C}H_2CHD_2$. Such sequences of isomeric transformations provide of course a very apt mechanism for explaining how isotopic mixing can take place; however, it remains to be seen as to what extent it can account for the essential features of the experimental evidence with respect to succinic acid.

One of the most remarkable features of the ESR spectra is that the only C-deuterated species observed[3] is $DOOCCHD\dot{C}HCOOD$ (or its O-hydrogen analogues). The mechanism of isotopic mixing through free radical isomers offers at once a general explanation of stereospecific mixing when we notice that mixing can only occur among the sites which the vacancy visits and any hydrogen atom sites from which it is precluded cannot participate in the mixing process. In crystalline succinic acid[6] the two hydrogen atoms of the CH_2 group are crystallographically distinct and the two CH_2 groups in the molecule are related by a centre of symmetry. Thus the hydrogen positions on the carbon backbone are of two distinct types. It is necessary for us to assume that hydrogen atom sites of one particular type are not visited by the vacancy and are thus precluded from the isotopic mixing. When the crystal is examined by ESR we observe the spectra of radicals, where the vacancy may be on either of the two " exchangeable " hydrogen positions. The unpaired electron couples with the two unexchanged H nuclei and with the nuclear spin of the hydrogen which happens to be on the fourth (exchangeable) position, which may be either that of H or D. The assumption that two (equivalent) sites on the carbon backbone are not visited by the hole leads at once to just the stereo-specific isotopic mixing observed in the ESR spectrum.

At this stage it is worth examining another well-attested case of isotopic mixing, namely that observed in alanine by Itoh and Miyagawa.[4] This differs from succinic acid in that the examination of the freshly irradiated partially deuterated crystal reveals no isotopically mixed species but only the radical $CH_3\dot{C}HCOOD$ (or its O-hydrogen analogue), which can be regarded as alanine from which a (deuterated) amino group has been removed. Storing the crystal at room temperature for two years or heating it for 2h at 100 °C causes the appearance of isotopically mixed species, viz. $CH_2D\dot{C}HR$ and/or $CH_3\dot{C}DR$ where R is presumably the carboxylic acid group. Only one deuteron appears on the carbon chain which is what one expects for isotopic mixing by isomeric transformations in the radical $CH_3\dot{C}HCOOD$ which has only one deuteron available to be transferred to positions where it can couple with the electron spin. More severe annealing, viz. 10h at 150 °C, causes changes in the spectrum consistent with the gradual appearance of species with more than one deuteron on the carbon chain until eventually a spectrum attributable to $CD_3\dot{C}DR$ alone is obtained. It is remarkable that the molecular fragment becomes completely deuterated, which can only occur if its hydrogen atoms are mixable with an effectively unlimited pool of deuterons. It is reasonable to agree with Itoh and Miyagawa that the polar deuterons of the crystal are exchangeable among themselves, presumably by an ionic mechanism akin to protonic conduction, and to add that a fairly obvious sequence of isomeric transformations offers a rational mechanism to explain the exchange between the four H nuclei which are coupled to the electron spin and the deuteron in the polar position. It seems evident from the data that transport to the carbon backbone proceeds more rapidly at 100 °C than the exchange mechanism which keeps the polar position deuterated.

Additional evidence that we can adduce as to the general correctness of this model of isotopic mixing comes from the observation in this laboratory of large scale isotopic mixing in crystals of OO′-dideuterosuccinic acid after treatment with moderate (5 Mrad) doses of radiation. The mixing proceeds to such an extent that it is easily observable in the infrared absorption spectrum which indicates that a large fraction of the hydrogen atom positions participate in the isotopic mixing. Not only are the very small number of free radicals involved but also the normal molecules of the crystal. The *G* value is about 500; such a large value pointing at once to a free radical chain reaction.

Experimental

Partially deuterated crystals of five compounds were prepared by recrystallizing three times from heavy water of 99.75% isotopic purity. The starting materials were succinic acid, (B.D.H. Analar and M. & B. Laboratory Reagent), alanine (B.D.H. Analar), glycine (B.D.H. Analar), dihydrothymine (City Chemical Corporation, N.Y.) and acetylglycine (synthesized according to Vogel[7] and checked for identity and purity by observing the melting point and by comparing the IR spectrum with that listed under the ASTM system). Selected crystals of each compound were cut in half and one half irradiated at room temperature with an X-ray dose of 5 Mrad from a Mo anode tube filtered with 0.005″ Al foil. Samples for IR absorption spectroscopy were prepared by the standard KBr disc technique, care being taken to ensure uniform treatment of the irradiated and unirradiated specimens at each stage. Using a Perkin-Elmer Model 237 IR absorption spectrophotometer the absorption spectrum of each substance both irradiated and unirradiated was obtained, as well as the differential spectrum of the irradiated material, with the relevant unirradiated specimen in the reference beam. In order to make the direct spectra immediately comparable with the differential spectra they were run without a compensating blank KBr disc in the reference beam. In four of the five cases no significant change could be detected in the spectra of the irradiated crystals either by comparison of the direct spectra or examination of the differential spectrum. Figure 1 (a), (b) and (c) illustrate the results for alanine. In the case of succinic acid however the IR spectrum of the irradiated crystal is found to be distinctly different from that of the unirradiated material, as shown in Fig. 1 (d), (e) and (f). The change in the spectrum was found to be consistently reproducible, most noticeable being the alteration in the strong bands indicated by arrows. The spectrum could be altered in these regions by doses as low as 1 Mrad. Post-irradiation annealing of the crystal for 6 hours at 100 °C produced no further change in the spectrum. When the spectra of irradiated and unirradiated crystals of undeuterated succinic acid were compared by the method described above the differential spectra showed only very small departures from perfect cancellation similar to those normally obtained in the comparison of nominally identical discs.

Discussion

The fact that the dosage of X-rays used caused significant changes in the IR spectrum of OO′-dideuterosuccinic acid crystals but not in the corresponding undeuterated crystals suggests at once that the appearance of the phenomenon is contingent upon partial deuteration and the possibility of isotopic mixing which then exists. The hypothesis that there is an extensive chemical reaction involving the production of new molecular species, or extensive polymerization, can be discounted from the fact that it should appear in both undeuterated and partially deuterated crystals. Furthermore, visual inspection of the irradiated crystals revealed them to be essentially unchanged in appearance; they remain water-clear, taking on a faint purplish colouration which fades rapidly and which appears to be unconnected with the ESR and IR spectra.

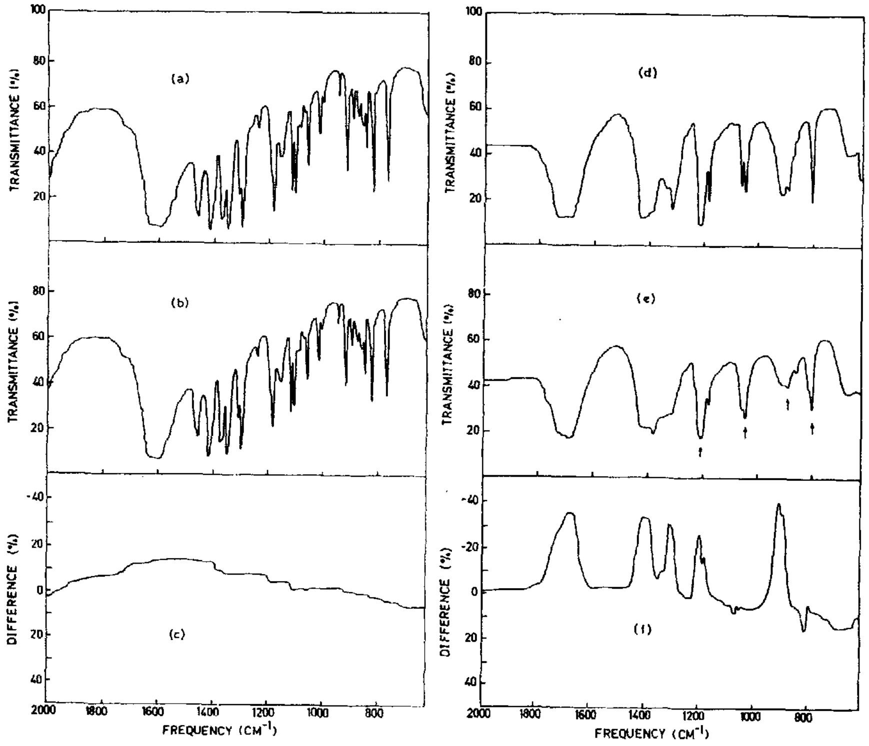

Figure 1. Comparison of IR absorption spectra of irradiated and unirradiated crystals of alanine and succinic acid (a) deuterated alanine + Kbr disc (b) irradiated deuterated alanine + Kbr disc (c) differential spectrum of the above (d) deuterated succinic acid + Kbr (e) irradiated deuterated succinic acid + Kbr, indicating regions where changes in the spectrum are prominent (f) differential spectrum of (d) and (e). The scales of the differential spectra are indicated percentages as shown on the instrument chart. They do not have a simple quantitative meaning in terms of changes in the absorbtivity of the specimen.

Our interpretation of the changes in the IR absorption bands is based on the band assignments of Shimanouchi *et al*[8] who examined IR spectra of four isotopic species of succinic acid in the crystalline state. Table 1 lists the relevant bands in the spectrum of $DOOCCH_2CH_2COOD$ together with the nature of the observed

TABLE 1 Changes in IR Absorption Spectrum of OO′-dideuterosuccinic Acid due to Irradiation

Band Frequency (cm^{-1})	Assignment	Change in absorption strength after irradiation
1435	CH_2 bend	—
1240	CHD bend	+ (?)
1210	CH_2 wag	—
1190	CHD wag	+
1180	CH_2 twist	—
1060	CHD twist	+
1050	OD in-plane def.	— (?)
910	OH out-of-plane def.	+
860	C—C stretch (for —CH_2—CH_2—)	— (?)
830	C—C stretch (for —CHD—CHD—)	+
805	CH_2 bend	—

change in absorption. Also included are the newly appearing bands due to the production of the molecular groups —CHD— and —CHDCHD—. It will be seen that the changes are just what one would expect for isotopic mixing between the H and D positions. In view of the extent of the changes, together with the fact that IR spectroscopy does not sensitively reveal impurities present in low concentration one must conclude that exchange has occurred in a large fraction of the molecules present in the crystal. It is clear that it is not only the few free radicals present which are involved. Indeed in the case of alanine (Fig. 1, (a) (b) and (c)) even after annealing, which is known to cause isotopic mixing in the free radicals it was found, in agreement with Itoh and Miyagawa[4] that no significant effect could be observed in the IR spectrum. As remarked above such a gross transformation points to a free radical chain reaction as the only reasonable way of explaining the large G value. What this could amount to in the case of a molecular crystal is essentially the following sequence of events. The radiation produces free radicals by knocking off hydrogen atoms to produce hydrogen vacancies, which promote isotopic mixing on the molecules where they reside. The vacancies are transferable from molecule to molecule by the mechanism of hydrogen atom abstraction and thus constitute a mobile crystal defect of a unique type for which the present authors have coined the name " kenon ".[9] Isotopic mixing is promoted on all molecules visited by the hydrogen vacancies either during the intermolecular transfer process or whilst resident on each molecule. The eventual fate of the hydrogen vacancies is presumably to destroy each other by the formation of a covalent bond when they arrive in pairs on adjacent molecules or even on the same molecule. It may be that the free radicals observed by ESR represent those hydrogen vacancies that have escaped self-destruction by becoming locked in special sites in the crystal. The mobility of the radical state by hydrogen vacancy diffusion offers an explanation of the mechanism by which free radicals are removed by thermal annealing which may proceed at quite low temperatures.[10,11]

In the case of succinic acid there are some particular features which must be dealt with in detail. It is convenient to collect here the facts which must either be accounted for or may have some bearing on the problem.

(1) The isotopic mixing is stereospecific.[3]

(2) The ratio $—CH_2\dot{C}H—/—CHD\dot{C}H—$ is observed[3] to be about 1:3.

(3) When irradiated and observed at 90 °K the dominant feature of the ESR spectrum is a single line presumably attributable to $DOOCCH_2CH_2CO\dot{O}$ or its O-hydrogen analogue.[3]

(4) Crystals of succinic acid and OO′-dideuterosuccinic acid prepared in this laboratory and irradiated at room temperature showed without exception the above single line superimposed on the spectrum as reported by other workers.[12,13]

We have found it difficult to construct a simple scheme consistent with all of these observations. If, to account for the stereospecificity, one requires two of the backbone H positions be not visited by the vacancy and so be precluded from the isotopic mixing. Specific predictions of the $—CH_2\dot{C}H—/—CHD\dot{C}H—$

ratio follow which differ according to whether we assume that the free radicals observed are made either by D or H bond breaking and subsequent isomeric transformations. However, on closer examination of the problem it emerges that we must consider our model for isotopic mixing in the light of the peculiar structure of the succinic acid molecule and crystal.[6] This is displayed sufficiently well for our purposes by Fig. 2 which represents the general topology of a single one of the parallel chains which make up the crystal lattice of OO′-dideuterosuccinic acid. Sites presumed to participate in the isotopic mixing are marked by an asterisk. If we imagine a hydrogen vacancy on one of these positions and confined to one molecule then a simple examination shows that its subsequent motion between available sites on the molecule produces only a modest amount of isotopic mixing. Complete shuffling of the three hydrogens that the vacancy mobilises is not achieved because the order in which they appear reading from one end of the molecule to the other cannot be altered. Furthermore, although isotopic mixing can occur in the sense that a D atom can be brought onto the carbon backbone, both of the free radical isomers which have the hydrogen vacancy on the backbone would, in the ESR spectrum, show coupling of the electron spin exclusively with protons, in contradiction of the fact that $-\mathrm{CHD\dot{C}H}-$ is prominent in the spectrum. It would appear therefore that it is necessary to invoke the transfer of vacancies from molecule to molecule with the increased scope for isotopic mixing that is entailed.

Considerations along these general lines lead us to propose the following outline for the process of isotopic mixing in this solid. The primary act of the radiation is regarded as being the production of hydrogen atom vacancies which are immediately mobile and travel a large distance, whether along the length of the chains of molecules or transverse to them being an open question. The evidence above is consistent with the radical $\mathrm{DOOCCH_2CH_2CO\dot{O}}$ being the major initial product of the radiation, which amounts to saying that the vacancies are produced on the deuterated positions. The passage of a single vacancy along a path, say, down a chain of

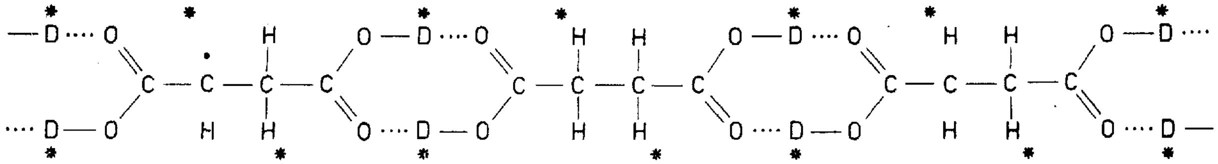

Figure 2. Schematic diagram of the arrangement in a chain of molecules in the succinic acid crystal. Positions postulated to be exchangeable are marked with an asterisk, one of these positions being shown as occupied by a hydrogen vacancy.

molecules results in the movement of all the hydrogens backward by one position. Most of the hydrogen atom vacancies are lost by their mutual destruction and only a few survive by being locked at crystal imperfections or in other special sites. One might hope to derive the $—CH_2\dot{C}H—/—CHD\dot{C}H—$ ratio theoretically from a consideration of the relative numbers of H and D atoms available for mixing. However, to attempt this at present involves many uncertainties, not the least of which is the question as to whether the free radicals actually observed in the crystal are truly representative of those one imagines to be present in a perfect model crystal. Further evidence as to how complicated the set of irradiation and post-irradiation events may be is provided by reports[14,15] of a further two radicals present as minor products of the irradiation of succinic acid viz. $CH_3\dot{C}HCOOH$ and $\dot{C}H_2CH_2COOH$ which are respectively the α- and β-keno-propionic acids according to the keno nomenclature.[9]

At this stage, however, it is worth noticing one point of interest, viz. that the radical $DOOCCHD\dot{C}HCOOD$ (or its O-hydrogen analogues) is the only isotopically mixed species revealed by the ESR. As far as the molecules which suffer isotopic mixing are concerned, it is quite possible that the saturated molecule $DOOCCHDCHDCOOD$ is present. According to our model the presence of this species could not be revealed by ESR because if it received a hydrogen vacancy it can only do so on one of the deuterated positions (i.e. by displacing one of the deuterons) and coupling of the electron spin with two deuterons cannot be achieved. A close examination of our IR data does not allow us to say more than that it could possibly be present.

Summary and Conclusions

A general model for isotopic mixing in irradiated organic crystals has been put forward. The mixing may involve only the free radicals themselves, when it proceeds by means of a sequence of isomeric transformations. This appears to be the case in alanine, where the experimental evidence points additionally to the existence of mutual exchange among the polar hydrogen positions in the crystal. If the radical state can be transferred from molecule to molecule by means of hydrogen atom abstraction then large scale isotopic mixing may occur involving the ordinary molecules as well as the free radicals. This appears to be what is observed in succinic acid. The evidence appears to indicate that the radical state may sometimes be mobile in organic crystals and can be regarded as constituting a remarkable new type of crystal defect, the kenon or hydrogen atom vacancy.

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REFERENCES

1. Gordy, W. and Miyagawa, I., *Bull. Am. Phys. Soc.* **5**, 253 (1960).
2. Miyagawa, I., Kurita, Y. and Gordy, W., *J. Chem. Phys.* **33**, 1599 (1960).
3. Pooley, D. and Whiffen, D. H., *J. Chem. Soc.* Pt. I, 366 (1962).
4. Itoh, K. and Miyagawa, I., *J. Chem. Phys.* **40**, 3328 (1964).
5. Morton, J. R., *J. Am. Chem. Soc.* **86**, 2325 (1964).
6. Kitaigorodskii, A., Organic Chemical Crystallography (Consultants Bureau, N.Y., 1961), p. 283.
7. Vogel, A. I. (1956) A Textbook of Practical Organic Chemistry. Longmans, Green & Co.
8. Shimanouski, T., Tsuboi, M., Takeniski, T. and Iwata, N., *Spectrochima Acta*, **16**, 1328 (1960).
9. Ericson, L. G. and Cutten, D.R., *Bull. Chem. Soc. Japan* **40**, 2974 (1967).
10. Cutten, D. R. and Ericson, L. G., International Conference on Electron Diffraction and the Nature of Defects in Crystals, Melbourne IIA-2. 1965.
11. Ericson, L. G. and Cutten, D. R., to be published.
12. McConnell, H. M. and Heller, C., *J. Chem. Phys.* **32**, 1535 (1960).
13. Pooley, D. and Whiffen, D. H., *Mol. Phys.* **4**, 81 (1961).
14. Read, S. F. J. and Whiffen, D. H., *Mol. Phys.* **12**, 159 (1967).
15. Klinck, R. A., *J. Chem. Phys.* **49**, 4722 (1968).