The Photo-Enolization of β-Disubstituted αβ-Unsaturated Ketone

Masaru TADA and Kyo MIURA

Department of Chemistry, School of Science and Engineering, Waseda University, Shinjuku, Tokyo 160

(Received May 27, 1975)

γ-Methyl groups of mesityl oxide (I), dypnone (II), 2-isopropylidenecyclopentanone (III), and pulegone (IV) were deuterated by ultra-violet irradiation in methanol-d. It has been claimed that these ketones are not enolized by photo-excitation, but the formation of enol by irradiation was proved by infrared spectroscopy at a low temperature and was correlated to the photo-deuteration. The photo-enolization was deduced to occur from an n–π* singlet excited state.

It has previously been reported that several β-disubstituted α,β-unsaturated ketones such as mesityl oxide(I) do not isomerize to β,γ-unsaturated ketones upon ultraviolet irradiation;[1–4] Yang and Jorgensen[1] attributed the photo-stability of mesityl oxide (I) to the π–π* nature of the lowest triplet excited state, which was proposed to have no ability to abstract γ-hydrogen.[5] This conclusion was drawn on the basis of a comparison with the behavior of the *ortho*-alkylated aromatic ketone, in which an n–π* triplet state has been proved to be responsible for photo-enolization by flush photolysis.[6] This deduction does not, however, seem proper since the nature of the excited state is very different between aliphatic and aromatic ketones, especially in the efficiency of intersystem crossing. A recent publication by Turro et al.[7] has demonstrated that the n–π* singlet and triplet excited states of adamantanone have the same degree of reactivity toward intermolecular hydrogen abstraction and that the lower effectiveness of the singlet excited state is attributable to its short life-time.

In this paper we wish to report on the general photo-enolization of β-disubstituted α,β-unsaturated ketones, which have no tendency to isomerize to β,γ-unsaturated ketones; an n–π* singlet state is responsible for the hydrogen transfer.

Experimental

Materials. Commercially available mesityl oxide (I) (bp 130 °C) and pulegone (IV) (bp 103 °C/17 mmHg) were purified by distillation. Dypnone (II) (bp 141—144 °C/0.3 mmHg) was prepared by the base-catalyzed condensation of acetophenone.[8] 2-Isopropylidenecyclopentanone (III) (bp 90—91 °C/14 mmHg) was prepared by the condensation of acetone with cyclopentanone.[9] The purity of these materials was checked by glc analysis (SE-30 and Carbowax 20 M on Chromosorb W, N_2) before use. UV λ nm (ε): I, 252 (3600), 314 (60); II, 295 (15800); III, 252 (3650), 325 (68); IV, 252 (6450), 324 (40). NMR (JEOL ps-100 spectrometer) of ketones (I, III, and IV) in MeOD show two signals due to *syn* and *anti*-methyls at 1.83 and 2.05 ppm for I, at 1.78 and 2.12 ppm for III, and at 1.72 and 1.98 ppm for IV, respectively, by using TMS as an internal reference. Dypnone (II) originally showed one signal at 2.53 ppm due to the methyl group of the *E*-form, but rapid photo-equilibration between *E* and *Z*-forms occurred upon irradiation and another signal appeared at 2.25 ppm.

Deuterium Exchange. Each ketone (I, II, III, or IV) was dissolved (2%) in MeOD containing 1% of TMS as an internal reference for the chemical shift and the signal intensity. The solution was then sealed in a Pyrex NMR sample

tube and irradiated by a 450-W medium-pressure Hg lamp—the distance between lamp and tube was *ca.* 1 cm. The NMR spectrum of the irradiated sample was inspected periodically. The relative intensities of the signals of the methyl groups to that of TMS were decreased by irradiation, as is shown by Figs. 1 and 2 in the text. Another sample tube wrapped with aluminum foil was placed in the irradiation apparatus as a reference. The reference sample did not show any change in its NMR spectrum. The solutions of the ketones in MeOH instead of MeOD were also irradiated under the same conditions, but their NMR spectra were identical with those of the non-irradiated solutions. Glc analyses of the samples also showed a quantitative recovery of the starting ketones.

Acid-catalyzed Deuteration. A solution of a ketone (I, II, III, or IV) in MeOD containing HCl (0.01 mol/l) was sealed in an NMR sample tube and kept under the same conditions as in photodeuteration, but without irradiation; the NMR spectra were taken periodically. The spectra showed no decrease in the signal intensities of the γ-methyl groups, but the signal intensities of the α-methyl group of mesityl oxide (I) at 2.05 ppm and of the α-methylene groups of the III and IV ketones at around 2.5 ppm were decreased—a 50% decrease within 15 hr for the I ketone.

Triplet Quenching of the Photo-deuteration. The solutions (2%) of dypnone (II) and pulegone (IV) in MeOD containing 0.0 and 0.1 mol/l of 3,3,4,4,-tetramethyl-1,2-diazetine 1,2-dioxide[10] were placed in a merry-go-round-type irradiation apparatus and were irradiated by means of a 450-W medium-pressure Hg lamp—the distance between lamp and tube was 5 cm—for 35 min (II) and 5 hr (IV). The irradiation caused the deuteration of γ-methyl groups (*ca.* 15% for II and *ca.* 30% for IV), and the quencher did not show any effect on the rate of deuteration of the γ-methyl groups.

Low Temperature Infrared Spectra. Pulegone (IV) dissolved in the mixed solvent of methyl cyclohexane and 2-methyltetrahydrofuran (2: 1) was placed in an infrared cell of CaF_2 plate, and the cell was mounted in the ditch of a brass block connected to a container of liquid nitrogen. The sample was hang in a glass case with a window of CaF_2 and was cooled by liquid nitrogen, with an occasional evacuation of the system. After a tight matrix of the sample has been obtained, the system was evacuated continuously (*ca.* 10⁻³ mm Hg). Pulegone (IV) in the cold matrix showed the absorptions at 1675 and 1615 cm⁻¹ due to the carbonyl group and the carbon-carbon double bond respectively. An external irradiation of the matrix through the window was carried out by means of a 500-W high-pressure Hg lamp mounted in a lamp house equipped with an optical system of a quartz lens and a Pyrex filter. Irradiation caused a diminution of the original absorptions, with a concomitant increase in new absorptions at 1664 and 1596 cm⁻¹ due to the enol form of IV (see Fig. 3); the photo-equilibrated state was attained after 2 hr.

In the case of mesityl oxide (I), the solvent system of methyl-

cyclohexane-2-methyltetrahydrofuran–isopentane(1 : 1 : 2) was superior to the system used for pulegone (IV). The original absorptions at 1695 and 1622 cm⁻¹ due to the s-cis form of ketone I, and at 1690 and 1645 cm⁻¹ due to the s-trans form of I, decreased, with a concomitant increase in the absorptions at 1655 and 1602 cm⁻¹ due to the enol form of I. The spectral change in mesityl oxide (I) was slower than that of pulegone (IV); it required irradiation for 10 hr to reach the photo-equilibrated state. The samples were warmed slowly after irradiation, and the spectral measurements were repeated during the period of warming up. Only the original absorptions were observed in the infrared spectrum of the warmed sample; the absorptions due to the enol form disappeared completely.

Results and Discussion

We found that, upon ultraviolet irradiation, β-disubstituted α,β-unsaturated ketone enolizes to dienol, and that the lack of the isomerization of the dienol to a β,γ-unsaturated ketone accounted for the nominal inertness of such a ketone. This result was established by the following experimental results. Each solution of mesityl oxide (I), dypnone (II), 2-isopropylidenecy-clopentanone (III), and pulegone (IV) in methanol-d was irradiated, and the photo-deuteration of the γ-methyl groups was examined by NMR. The relative intensities of the signals versus irradiation period are shown in Figs. 1 and 2 A reference experiment in the dark did not show deuteration to any detectable extent, and the irradiations of I—IV the ketones in methanol resulted in a quantitative recovery of the starting materials. There is a possibility that a kind of acidic compound formed by the irradiation of methanol-d containing a trace amount of oxygen[11] would catalyze the deuteration of γ-methyl groups. The addition of hydrochloric acid (0.01 mol/l) to the solution, however, caused only the deuteration of the α-methylene or α-methyl groups; no deuteration of γ-methyl groups was observerd.

The photo-enolization was proved more directly by the infrared spectrum the dienol isolated in a cold matrix.

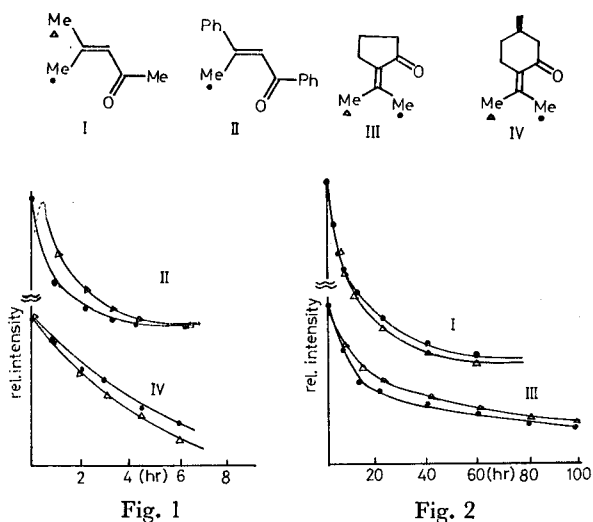Fig. 1   Fig. 2

Fig. 1 and 2. Decrease of NMR signal-intensities of α-methyls versus irradiation period.

Pulegone (IV) dissolved in methylcyclohexane-2-methyl-tetrahydrofuran (2 : 1) was solidified to a clear matrix under cooling by liquid nitrogen. The irradiation of the matrix caused a distinct change in its infrared spectrum, as is shown in Fig. 3. The absorptions due to the starting pulegone (IV) at 1675 ($\nu_{C=O}$) and 1615 cm⁻¹ ($\nu_{C=C}$) decreased, with a concomitant increase in the absorptions at 1664 ($\nu_{C=O}$) and 1596 cm⁻¹ ($\nu_{C=C}$, strong) due to the enol form of pulegone. The same spectroscopic behavior was observed with mesityl oxide (I), in which the absorptions at 1655 ($\nu_{C=O}$) and 1602 cm⁻¹ ($\nu_{C=C}$, strong) increased, with a concomitant decrease in the absorptions at 1695 ($\nu_{C=O}$) and 1622 cm⁻¹ ($\nu_{C=C}$) for the s-cis form of I and at 1690 ($\nu_{C=O}$) and 1645 cm⁻¹ ($\nu_{C=C}$) for the s-trans form of I.[12] In accordance with the difference in the rate of photo-deuteration between the I and IV ketones, the photo-equilibrium state of IV was attained after 2 hr, whereas that of I required 10 hr. The original absorptions for I and IV were regenerated by warming up the sample after the termination of the irradiation.
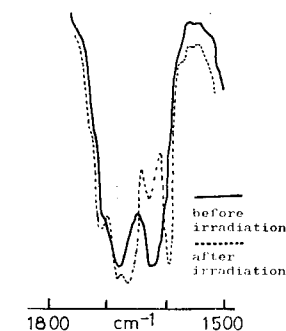
Fig. 3. Infrared spectra.

These experimental findings are compatible with Scheme 1. The deuterium exchange of the hydroxy group of the enol and the hydrogen return to the γ-carbon explain the photo-stability in the non-deuterated methanol and the deuterium exchange of the γ-methyl groups of these ketones. It is worthwhile to point out that the prototropy in these ketones, upon ketonization, takes the 1,5-migration instead of the 1,3-migration path to give β,γ-unsaturated ketone. This behavior can be explained by considering that the prototropy is completely intramolecular and that the 1,5-transfer is more favorable in the energy surface of the reaction. Dypnone (II) and pulegone (IV) isomerize to β,γ-unsaturated isomers upon irradiation in the presence of hydrochloric acid[13]; this feature can be accounted for by the intermolecular prototropy
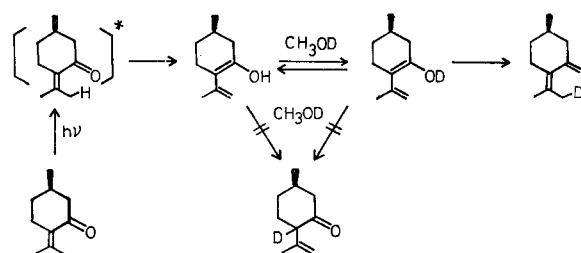
Scheme 1

placing a proton at the α-position of the enol.[14,15]

We deduced the excited state responsible for the photo-enolization to be the n–π^* singlet. This conclusion is based on a consideration of the relation between the rate of enolization and the geometry of the ground state of these ketones, and by triplet-quenching experiments. The deuterations of dypnone (II) and pulegone (IV) are much faster than those of mesityl oxide (I) and 2-isopropylidenecyclopentanone (III); this property is considered to be a reflection of the geometry of the ground state.[16,17] Judging from the Dreiding molecular model, the shortest distance between carbonyl oxygen and one of the hydrogens of γ-methyl is 1.9 Å for the III ketone and 1.5 Å for the IV ketone when the conjugate system takes a planar conformation. The influence of the ground-state geometry on the reaction rate can be expected only in the singlet state immediately after excitation. In the case of acyclic ketone, we propose that the difference in the rates of the deuteration of the I and II ketones is a reflection of the coplanarity of the enone system. The II ketone is more coplanar than the I ketone due to the conjugate effect of the aromatic ring. Another possibility is the consequence of the difference in absorbance (ε: I, 60 at 314 nm; II, 15800 at 295 nm). The large absorption coefficient of the II ketone indicates that both the lowest singlet and triplet states are π–π^* in nature, but the efficiency for hydrogen abstraction by the π–π^* state is, in general, very low. Therefore, we feel that the higher-lying n–π^* state instead of the π–π^* state is responsible for the photo-enolization of II, and that the coplanarity of the system is more crucial.

The photo-deuterations of dypnone (II) and pulegone (IV) were not quenched by a triplet quencher, 3,3,4,4-tetramethyl-1,2-diazetine 1,2-dioxide ($E_T=ca.$ 40 kcal/mol);[10] therefore, the photo-deuteration via photo-enolization must be a singlet or an extremely fast triplet process. It has been established that an n–π^* singlet state abstracts hydrogen as fast as an n–π^* triplet state does.[7] The fast formation of a photo-equiliblium mixture of the E and Z forms of dypnone (II), as well as the deuteration of both methyl groups of the I, III, and IV ketones at a similar rate, shows the existence of fast geometrical isomerization from the excited state with a triplet manifold. This free rotor effect[18-20] must be responsible for the dissipation of the triplet excited energy, and the present phot-deuteration must be a singlet process.

In conclusion, it follows from the present results that the isomerization of an α,β-unsaturated ketone into a β,γ-unsaturated ketone is not a definite guide for the usefulness of photo-enolization, as has previously been reported, and that the γ-hydrogen abstraction in the I—IV ketones is a fast process from the singlet n–π^* state, retaining the geometry of the ground state.

References

1) N. C. Yang and M. J. Jorgensen, Tetrahedron Lett., 1964, 1203.

2) P. J. Wagner and G. S. Hammond, J. Amer. Chem. Soc., 88, 1245 (1966).

3) L. F. Friedrich and G. B. Schuster, ibid., 91, 7204 (1969).

4) D. R. Morton and N. J. Turro, ibid., 95, 3947 (1973).

5) N. C. Yang, "Reactivity of the Excited State Organic Molecule," Interscience Publishers, London (1967), p. 145.

6) E. F. Zwicker, L. I. Grossweiner, and N. C. Yang, J. Amer. Chem. Soc., 85, 2671 (1963).

7) D. R. Chorney, J. C. Dalton, R. R. Hantala, J. J. Snyder, and N. J. Turro, ibid., 96, 1407 (1974).

8) N. O. Calloway and L. D. Green, ibid., 59, 809 (1937).

9) G. Vovon and A. Apchie, Bull. Soc. Chim. Fr., 43, 667 (1928).

10) E. F. Ullman and P. Singh, J. Amer. Chem. Soc., 94, 5077 (1972).

11) S. J. Crist, G. A. Lee, and A. L. Noreen, Tetrahedron Lett., 1971, 4175.

12) L. J. Bellamy, "Advances in Infrared Group Frequencies," Methuen and Co., London (1968), p. 34.

13) Private communication from Prof. T. Sato of Waseda University.

14) D. Bellus, D. R. Kerns, and K. Schaffner, Helv. Chim. Acta, 52, 97 (1969).

15) P. Margaretha and K. Schaffner, ibid., 56, 2884 (1973).

16) F. D. Lewis and B. W. Johnson, J. Amer. Chem. Soc., 94, 8914 (1972).

17) F. D. Lewis and B. W. Johnson, Tetrahedron Lett., 1973, 2557.

18) J. S. Swenton, A. R. Crumrine, and T. J. Walker, J. Amer. Chem. Soc., 92, 1406 (1970).

19) H. E. Zimmerman and A. C. Pratt, ibid., 92, 1407 (1970).

20) K. G. Hancock and R. O. Grider, Tetrahedron Lett., 1972, 1367.