

6. A. Williams, *Acc. Chem. Res.* **17**, 425 (1984).
7. These relations, (12), correspond to eq. (11) of ref.(3).
8. E. S. Lewis, and S. Kukes, *J. Am. Chem. Soc.* **101**, 417 (1979).
9. For this reaction, $\rho_{ii} = 0.60$ and $\rho_e = 2.94^5$ give the correct values of $\rho^+ = \rho^L = \rho_{Hi} = 1.77$ and $\rho^- = \rho^N = \rho_{iH} = -1.17$, which differ from ρ values given in ref. (4). Their values are really for ρ_{Xi} and ρ_{iX} , where $X = 3,5\text{-Cl}_2$, which are in general different from ρ_{Hi} and ρ_{iH} , since eq. (1) leads to $d \log k_{Xi}/d \sigma_i = \rho_{Hi} + \rho_{Xi} \sigma_X$ whereas $d \log k_{Hi}/d \sigma_i = \rho_{Hi}$. Thus the discrepancy between $\rho_{ii} = \rho^+ + \rho^- = +0.73$ and $\rho_{ii} = +0.6$ by direct determination is not really due to an uncertainty but originates from misconception.
10. J. M. Wilson, R. J. Bayer, and O. J. Hupe, *J. Am. Chem. Soc.* **99**, 7922 (1977).
11. G. Petrillo, M. Novi, G. Garbarino, and C. Deil 'Erba, *J. Chem. Soc., Perkin 4*, 1741 (1985).
12. The methylation equilibrium⁴ in example (ii) above is much better than the protonating equilibrium normally used^{13,14} as a standardizing equilibrium⁶ in this case, although the reaction center is not a methyl carbon.
13. B.-L. Poh, *Can. J. Chem.* **57**, 255 (1979).
14. R. V. Hoffman and J. M. Shaukweiler, *J. Am. Chem. Soc.* **108**, 5536 (1986). To be more rigorous, the $\text{p}K_{lg}$ values given in this paper should be revised to a new correct set based on K_{Hi} values, i.e., $\text{p}K_{lg} = -\log K_{Hi} = -2.94 \sigma_p$, since $K_{Hi} \neq K_{Xi}$ where $X = 3,5\text{-Cl}_2$. However, determination of β values can be more easily achieved by dividing ρ values by $\rho_e = 2.94$ so that the $\text{p}K_{lg}$ values are not really needed; it is far easier and more natural to plot $\log k$ vs σ_i than to plot $\log k$ vs $\text{p}K_{lg}$.

Photo-enhanced Reduction of Conjugated Enones with NaBH_4

Sang Chul Shim* and Ho Seop Yeo

Department of Chemistry, Korea Advanced Institute of Science and Technology, Seoul 131. Received March 9, 1987

The reduction of some cyclic conjugated enones with electron-donating substituent on C-3 by sodium borohydride was accelerated on irradiation. The photo-enhanced reduction seems to undergo through zwitterionic species formed from the (n, π^*) triplet state of conjugated enones, followed by hydride attack to yield unsaturated or saturated alcohols.

Introduction








There have been some attempts to change the reactivities of metal hydrides by photo-excitation.^{1,2,3} Wittkop and his coworkers reported enhanced reduction of steroidal ketones by sodium borohydride on irradiation with UV light.⁴ It was also recently reported that cyclohexanones were nearly quantitatively reduced to cyclohexanols by sodium borohydride in diglyme on irradiation.⁵ The compounds are inert or very slowly reduced under the same condition without irradiation.

Stimulated by these results, we examined the photo-enhanced borohydride reduction of conjugated enones by sodium borohydride.

Results and Discussion

The effect of UV light on the reduction of various conjugated enones by sodium borohydride was studied and the results are shown in Table 1. Irradiation had no influence on the reduction of acyclic and cyclic conjugated enones studied except 3-methyl cyclic enones. The conversion yields of reduction of **4**, **5**, and **6** to saturated or unsaturated alcohols without irradiation were 12, 68, 41% in 2 h, but increased up to 82, 99, and 100% on irradiation under the same conditions. Different from the other enones, the enones which have

Table 1. Light Effect on the Reduction^a of Various Enones with Sodium Borohydride

Entry No.	Compound	Conversion ^b Yield (%) h	Δ
1		42	43
2		8	7
3		33	35
4		82	12
5		99	68
6		100	41
7		68	68

^aIrradiation of enones for 2h at room temperature except **1** and **4** which were irradiated for 1 h. ^bYield of reduced alcohol (sum of saturated and unsaturated alcohol produced).

photocatalyzed effect are cyclic and have a methyl group on C-3. Since the difference of **5** from **3** is only the 3-methyl

*Dedicated to Professor Nung Min Yoon on the occasion of his 60th birthday.

Table 2. Photocatalyzed Reduction^a of 3-Substituted Cyclohexenone Derivatives

Entry No.	Compound		Conversion Yield (%)	Quantum Yield
4	R = CH ₃	hν	82	0.83
		Δ	12	
8	R = OCH ₃	hν	34	0.12
		Δ	0	

^aIrradiation, 4; 2h. 8; 3h.**Table 3. Selectivity of Photoreduction**

Compound		1,2-addition (%)	1,4-addition (%)	1,2/1,4
4	hν	80	15	5.3
	Δ	62	38	1.6
5	hν	42	58	0.7
	Δ	43	57	0.8

Table 4. Quenching of Photoreduction of Isophorone by Piperylene

Concentration of Piperylene	Conversion Yield(%)	Quantum Yield
0	6 ^a	
0	55	0.27
4 × 10 ⁻³ M	50	0.24
8 × 10 ⁻³ M	48	0.23
1.2 × 10 ⁻² M	46	0.22
1.6 × 10 ⁻² M	41	0.19

^aBlank Thermal Reduction.

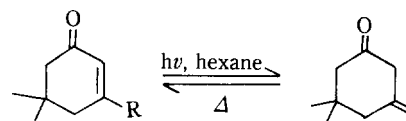
group, it is clear that 3-methyl group plays an important role in photocatalyzed reduction. To elucidate the role of 3-methyl group, substituent effect was investigated as shown in Table 2. The conjugated enones with 3-Cl and 3-Br were also investigated at 254 and 313 nm but the major photoproduct (over 80%) was not reduction product. It is not surprising since irradiation of halogen compounds gives hydrocarbons via free radical chain mechanism⁶ due to C-halogen bond homolysis. In the case of R = CN, the reduction was not photochemically enhanced at both 254 and 313 nm. When R = OCH₃(**8**), the quantum yield was smaller than that of R = CH₃. But **8** was reduced only upto 2% without irradiation in 7 days at room temperature and the ratio of the rate constant of the photocatalyzed reduction to that of the thermal reduction for R = OCH₃ is much larger than that of R = CH₃. The electron-donating substituent on C-3 is thus necessary for the photocatalyzed reduction, suggesting that the photocatalyzed reduction undergoes through an intermediate which is electron deficient on C-3. **3** has no photocatalyzed effect but the reduction of **5** was much more accelerated on irradiation. This is attributed to the role of 3-methyl group which is not only electron-donating group but also the σ-bond of that delocalizes through the π-system very well. This is supported by the results that irradiation in 0.06M hexane solution at -13°C yields the deconjugated isomer as shown in Scheme 1.⁷ Irradiation of the deuterated derivatives (r = CD₃) gave isophorone containing deuterium

Table 5. Temperature Effect on the Photoreduction of 4^a.

Temperature		Conversion Yield (%)	Quantum Yield
0°	hν	27	0.30
	Δ	0	
30°	hν	60	0.54
	Δ	11	

^aIrradiation for 1h.**Table 6. The NaBH₄ Concentration Effect on the Photoreduction of 4^a**

Concentration of Sodium borohydride	Quantum Yield
0.5 eq.	0.23
1.0 eq.	0.26
2.0 eq.	0.26

^aIrradiation for 1 h.**Scheme 1**

at both C-2 and C-3 methyl groups.

Selectivities of thermal and photocatalyzed reduction are shown in Table 3. The ratio of 1,2/1,4 addition in the photocatalyzed reduction of **5** was not much different from that of the thermal reduction but was very much different in **4**. In the case of **8**, the selectivities could not be compared because **8** was unreactive in this condition.

The quenching of the excited state of conjugated enones by piperylene in 2 + 2 cycloaddition has been extensively studied. The results of quenching study by piperylene are shown in Table 4. The photocatalyzed reduction of **4** was efficiently quenched by piperylene. Stern-Volmer plots were invariably linear and the results agree with that intersystem crossing yields of cyclic conjugated enones are very high.^{8,9} This reaction, therefore, seems to proceed via a triplet state.

The temperature and sodium borohydride concentration effects were studied as shown in Table 5 and 6. The quantum yield of the reduction at 30°C was much larger than that at 0°C and the quantum yields scarcely changed as the concentration of sodium borohydride increased, indicating that the photoreduction includes a state which needs significant energy of activation and hydride attack does not occur at the rate controlling step implying the formation of zwitterionic intermediate from the triplet state in the rate controlling step.

The reduction of **4** was investigated in various solvents as shown in Table 7. Quantum yield increased as the viscosity of solvents increased, indicating that sodium borohydride interacts with the carbonyl group of isophorone in the ground state since the excited states of conjugated enones are more electron deficient on oxygen than the ground state¹⁰ and cage effect therefore may play an important role. To obtain some supporting evidence for the idea, salt effect on **8** was investigated since the Brønsted basicity of this enone is very large compared with other enones.¹¹ Quantum yield was greatly enhanced when 1 equivalent of lithium bromide was added to enone but addition of 4 equivalents did not affect

Table 7. Solvent Effect on the Photoreduction^a of 4

Solvent		Conversion Yield (%)	Quantum Yield	Viscosity
Acetonitrile	$h\nu$	23	0.12	0.34
	Δ	2		
Monoglyme	$h\nu$	39	0.17	0.455
	Δ	9		
Diglyme	$h\nu$	40	0.20	0.981
	Δ	3		
2-Propanol	$h\nu$	49	0.22	2.13
	Δ	8		

^aNaBH₄ is 0.5 eq. to isophorone.

Table 8. LiBr Effect on the Photoreduction of 8^a

Concentration of LiBr		Conversion Yield (%)	Quantum Yield
0 ^b	$h\nu$	34	0.12
	Δ	0	
0	$h\nu$	6	0.03
	Δ	1	
1 eq.	$h\nu$	20	0.10
	Δ	1	
4 eq.	$h\nu$	17	0.10
	Δ	1	

^aSolvent is 25% aq. acetonitrile. ^bSolvent is 2-propanol. All samples were irradiated for 3h.

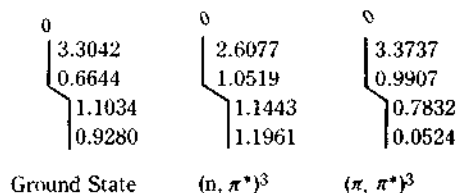


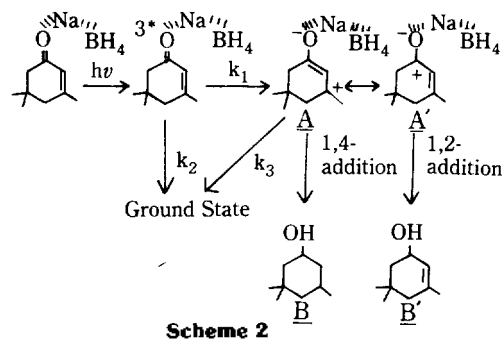
Figure 1. Calculated electron densities of $\alpha\beta$ -unsaturated ketones (electron densities at oxygen include Py contribution).

any further as shown in Table 8. This is attributed to the greater Lewis acid strength of smaller lithium cation than sodium. The more efficient and stronger the complexation of metal ion with the carbonyl group of the enone is, the more rapid the rate of the photocatalyzed reduction is. The effect of metal ion is very much pronounced as the photoreduction of **8** in 25% aqueous acetonitrile was much slower than in 2-propanol because sodium borohydride in 2-propanol exists as ion pair as shown in Table 8, but as the dissociated ion in water because of the effective solvation of metal ion in water.¹² Therefore the complexation of metal ion with the carbonyl group is less effective in water than in 2-propanol and the metal ion cannot lower the activation energy in water as much as in 2-propanol.

Conjugated enones have two triplet excited states; (n, π^*) and (π, π^*) triplet states. Zimmerman and his coworkers calculated electron densities of ground and excited states of a conjugated enone as shown in Figure 1. The (n, π^*) triplet state is more electron deficient on oxygen than in the ground state and the complex of sodium borohydride with carbonyl group of an enone can be broken in this excited state. If the

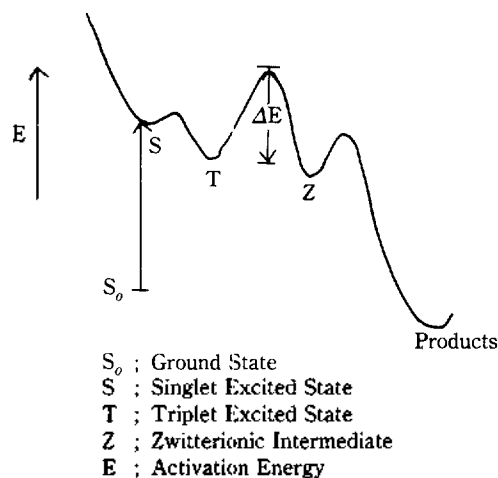
viscosity of a solvent is large, those broken from the complex could be in the solvent cage until the formation of zwitterionic species which is more electron rich on oxygen than in the ground state and the formation of the complex is more efficient supporting (π, π^*) triplet state as a reactive state.

From these data, a plausible mechanism for the photocatalyzed reduction is proposed as shown in scheme 2.



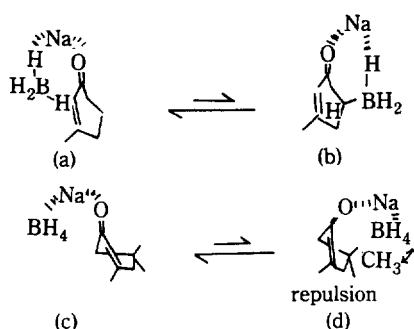
In Table 1, the reduction of acyclic conjugated enones was not enhanced on irradiation. It is not surprising because these enones do not undergo any reaction upon absorption of light. Their low reactivity might result from a rapid relaxation to an appreciably more twisted geometry in their triplet state than can be obtained in cyclic enones.¹³ The rate constant, k_2 , will, therefore, be much larger than k_1 and photocatalyzed effect cannot be detectable.

In case of cyclic enones, the photo-enhanced reduction was observed only in the enones which have electron-donating group on C-3. This is attributed to the activation energy difference as shown in Scheme 3. In the absence of electron-donating group, ΔE is large and k_2 is greater than k_1 and photocatalyzed effect is so small that is not detectable.



Scheme 3

Selectivities as shown in Table 3 slightly weaken this argument because the distribution of positive charge will be larger in C-3 than in C-1 in the zwitterionic intermediate. But 1,2-addition of hydride is through a stable six membered-ring transition state (a), while 1,4-addition is through a less stable 8 membered-ring transition state (b) as shown in Scheme 4. Furthermore, 1,4-hydride attack is possible in the less favorable form among many conformers. This is more obvious in isophorone in which the (c) form is much less



Scheme 4

favorable than (d) because the repulsion between borohydride and 5-methyl groups. Therefore, the ratio of 1,2-/1,4-addition in the photoreduction of **4** is larger than that in thermal reduction and the difference is much larger in **4** than in **5**.

Conclusion

The key structural feature of conjugated enones for the photocatalyzed reduction to occur is cyclic and 3-substituent which must be an electron-donating group because this photocatalyzed reduction undergoes through zwitterionic species formed from the (n, π^*) triplet state of enones. Viscous solvent is favored and aqueous solvent is not.

Experimental

Materials

All of the conjugated enones (**1**, **2**, **3**, **4**, **5**, **6**, and **7**) except specified otherwise were purchased from Aldrich Chemical Company and used after distillation. 3-Chloro-, 3-bromo-, 3-cyano- and 3-methoxy-5,5-dimethyl-2-cyclohexen-1-one were prepared as described in ref. 14, 15, and 16. Sodium borohydride and piperylene were purchased from Aldrich Chemical Company and used without further purification. Lithium bromide from Fluka Chemical Company was also used without further purification. Isopropyl alcohol and acetonitrile were dried with calcium hydride and distilled under the dry nitrogen atmosphere and stored under a slightly positive nitrogen pressure in a flask equipped with a rubber septum syringe inlet. Diglyme and monoglyme were dried with sodium and distilled and stored by the same method used for isopropyl alcohol.

Instruments

Spectra and Physical Data. Gas chromatographic (GLC) analyses of product mixture were carried out on a Varian 2800 Gas Chromatograph with a FID detector. All analyses were carried out on a 10ft \times 1/8 in. 10% Carbowax 20M (column). UV spectra were recorded on a Cary-17 spectrophotometer. IR spectra were obtained on a Perkin Elmer 267 spectrophotometer using potassium bromide pellet or sodium chloride window. ^1H nmr spectra were obtained on a Varian T-6JA nmr spectrometer in CDCl_3 . Mass spectra were obtained on a Hewlett Packard 5985A GC/MS system using electron impact (EI) method.

General Procedure of Photocatalyzed Reduction of

Conjugated Enones. Two oven dried rubber-capped quartz tubes were flushed with anhydrous nitrogen and 0.1 mmole of sodium borohydride in 2-propanol (2 ml) was introduced into each of the quartz tubes. In order to compare photocatalyzed and thermal reduction, one of the two quartz tubes was covered with aluminum foil to cut off the light. The reduction was started by the addition of 0.1 mmole of an enone in 0.5 ml of 2-propanol. The final solution was 0.04 M enone and 0.12 M hydride. The two mixtures were irradiated for 2 h in a merry-go-round with 254 nm and then hydrolyzed with 2 N aq. HCl, followed by neutralization with 2 N aq. NaOH. The two neutralized mixtures were saturated with potassium carbonate, shaken for a minute and left for an hour. These two reaction mixtures were analyzed by GLC.

Quantum Yield Measurement. The solutions were irradiated with Hanovia 450 W medium pressure arc lamp (Type 697A36) in a merry-go-round. Mercury emission line of 254 and 313 nm were isolated with filter solutions as described in ref. 17. Ferrioxalate actinometry was used to monitor the intensity of the exciting light.

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References

- G. Balle, P. Cerutti and Witkop, *J. Am. Chem. Soc.*, **88**, 3946 (1966).
- P. Yonemitsu, P. Cerutti, and B. Witkop, *J. Am. Chem. Soc.*, **88**, 3941 (1966).
- J.H. Choi, D.W. Kim, and S.C. Shim, *Tetrahedron Lett.*, **27**, 1157 (1986).
- J.A. Waters and B. Witkop, *J. Am. Chem. Soc.*, **90**, 758 (1968).
- D.C. Wigfield, S. Feiner, and F.W. Gowland, *Tetrahedron Lett.*, 3377 (1976).
- J.A. Barltrop and D. Bradbury, *J. Am. Chem. Soc.*, **95**, 5085 (1973).
- P.W. Jennings, Ph.D. Dissertation Univ. Utah, Salt Lake city, Utah Dissertation Abstra., **26**, 698 (1965).
- P.J. Wagner and D.J. Buchek, *J. Am. Chem. Soc.*, **91**, 5090 (1969).
- E.Y. Lam, D. Valentine, and G.S. Hammond, *J. Am. Chem. Soc.*, **89**, 3482 (1967).
- H.E. Zimmerman, R.W. Binkley, J.J. McCullough, and G.A. Zimmerman, *J. Am. Chem. Soc.*, **89**, 6589 (1967).
- M. Azzaro, J.F. Gal, and S. Geribaldi, *J. Org. Chem.*, **47**, 4981 (1982).
- H.C. Brown and K. Ichikawa, *J. Am. Chem. Soc.*, **83**, 4372 (1961).
- W.A. Noyes, G.S. Hammond and Pitts, "Advances in Photochemistry" Vol. 5.
- R.D. Clark and C.H. Heathcock, *J. Org. Chem.*, **29**, 636 (1976).
- W.R. Benson and A.E. Pohland, *J. Org. Chem.*, **29**, 385 (1964).
- E. Piers and Isao Nagakura, *Syn. Comm.*, **5**(3), 193 (1975).
- J.G. Calvert and J.N. Pitts, "Photochemistry" John Wiley and Sons, Inc., 1967.