

tetrahydrodiol epoxides. This feature must be of prime biological importance. Indeed, the chief chemical characteristics of the tetrahydrodiol epoxides are anticipated to be related to the electron-withdrawing properties of the two hydroxyl substituents.

It has been proposed that the "bay-region" tetrahydro epoxides of BP are particularly susceptible to solvolysis and nucleophilic attack owing to an enhancement in the stability of the benzylic carbocation formed upon ionic opening of the epoxide ring.²¹ Comparison of the bay-region tetrahydro epoxide **5** with its isomer **7** reveals that both k_0 and k_H are greater by ~3- to 5-fold for the bay-region isomer. However, the same feature may be noted for the 1,2- and 3,4-phenanthrene oxides (**6** vs. **8**) although the predominant products are phenols formed from *allylic* rather than benzylic carbocations.¹¹ Examination of Table I reveals that the second-order rate constants for reaction of the various epoxides with thiol anions are almost independent of the structure of the epoxide ($k_s = 0.17$ – $5.09 \text{ M}^{-1} \text{ s}^{-1}$; average $1.8 \pm 1.2 \text{ M}^{-1} \text{ s}^{-1}$). For this reason the nucleophilic susceptibility indices are determined primarily by k_0 . The order of NSI values (i.e., $7 > 5 > 2 > 8 > 6$ and $10 > 11 > 3 > 4$), if extrapolated to the similarly substituted BP derivatives, is broadly that of their carcinogenicity and mutagenicity. This is suggested to be related to either a relationship between k_0 and k_m/k_{cat} for the enzymes epoxide hydrase and glutathione conjugating enzyme²² or to the possibility that epoxides which are not scavenged by these enzymes are those which reach gene material and their success in doing so is accounted for by their NSI values. In this regard it is known that A and B are very poor substrates for epoxide hydrase.²³

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References and Notes

- D. M. Jerina, J. W. Daly, B. Witkop, P. Zaltzman-Nirenberg, and S. Udenfriend, *J. Am. Chem. Soc.*, **90**, 6525 (1968); *Biochemistry*, **9**, 147 (1970).
- S. K. Yang, P. P. Roller, and H. V. Gelboin, *Biochemistry*, **16**, 3680 (1977).
- P. G. Wislocki, A. W. Wood, R. L. Chang, W. Levin, H. Yagi, O. Hernandez, P. M. Dansette, D. M. Jerina, and A. H. Conney, *Cancer Res.*, **36**, 3350 (1976).
- M. Miyato, K. Shudo, Y. Kitahara, G.-F. Huang, and T. Okamoto, *Mutation Res.*, **37**, 187 (1976).
- P. G. Wislocki, A. W. Wood, R. L. Chang, W. Levin, H. Yagi, O. Hernandez, D. M. Jerina, and A. H. Conney, *Biochem. Biophys. Res. Commun.*, **68**, 1006 (1976).
- A. W. Wood, P. G. Wislocki, R. L. Chang, W. Levin, A. Y. H. Lu, H. Yagi, O. Hernandez, D. M. Jerina, and A. H. Conney, *Cancer Res.*, **36**, 3358 (1976).
- A. W. Wood, R. L. Goode, R. L. Chang, W. Levin, A. H. Conney, H. Yagi, P. M. Dansette, and D. M. Jerina, *Proc. Natl. Acad. Sci. U.S.A.*, **72**, 3176 (1975).
- E. Bresnick, T. F. McDonald, H. Yagi, D. M. Jerina, W. Levin, A. W. Wood, and A. H. Conney, *Cancer Res.*, **37**, 984 (1977).
- (a) S. K. Yang, H. V. Gelboin, B. F. Trump, H. Antrup, and C. C. Harris, *Cancer Res.*, **37**, 1210 (1977); (b) W. M. Baird and L. Diamond, *Biochem. Biophys. Res. Commun.*, **77**, 162 (1977); (c) K. W. Jennette, A. M. Jeffrey, S. H. Blobstein, F. A. Beland, R. G. Harvey, and I. B. Weinstein, *Biochemistry*, **16**, 933 (1977); (d) K. Alexander and M. H. Thompson, *Cancer Res.*, **37**, 1443 (1977); (e) H. W. S. King, M. R. Osborne, F. A. Beland, R. G. Harvey, and P. Brooks, *Proc. Natl. Acad. Sci. U.S.A.*, **73**, 2679 (1976); (f) A. M. Jeffrey, K. W. Jennette, S. H. Blobstein, I. B. Weinstein, F. A. Beland, R. G. Harvey, H. Kasal, I. Mima, and K. Nakamishi, *J. Am. Chem. Soc.*, **98**, 5714 (1976); (g) M. Koreeda, P. D. Moore, H. Yagi, H. J. C. Yeh, and D. M. Jerina, *ibid.*, **98**, 6720 (1976); (h) G. Lowengart and B. L. Van Duuren, *Tetrahedron Lett.*, 3473 (1976).
- W. M. Baird and L. Diamond, *Biochem. Biophys. Res. Commun.*, **77**, 162 (1977).
- (a) P. Y. Bruice, T. C. Bruice, H. Yagi, and D. M. Jerina, *J. Am. Chem. Soc.*, **98**, 2973 (1976); (b) for a recent compilation see P. Y. Bruice and T. C. Bruice, *Biochemistry*, **17**, in press.
- M. D. Burke, H. Vadl, B. Jernström, and S. Orrenius, *J. Biol. Chem.*, **252**, 6424 (1977).
- T.C.B. has not felt that the available facilities would allow study of the highly carcinogenic BP analogues.
- (a) P. Y. Bruice and T. C. Bruice, *Acc. Chem. Res.*, **9**, 378 (1976); (b) F. A. Long and J. G. Pritchard, *J. Am. Chem. Soc.*, **78**, 2663 (1956); (c) C. H. Rochester, "Acidity Functions", Academic Press, New York, N.Y., 1970, p 138.

- P. Y. Bruice and T. C. Bruice, *J. Am. Chem. Soc.*, **98**, 2023 (1976).
- Determined as previously described: G. J. Kasperek and T. C. Bruice, *J. Am. Chem. Soc.*, **94**, 198 (1972).
- The pK_a values of amines are decreased by ~1.0 upon α,β unsaturation and by ~0.5 upon β,γ unsaturation: H. K. Hall, *J. Am. Chem. Soc.*, **79**, 5441 (1957); J. Clark and D. D. Perin, *Quant. Rev.*, **18**, 313 (1964). The value of ρ_1 for this system (after converting from ρ^* to ρ_1 employing a correction factor of 6.23 (M. Charton, *J. Org. Chem.*, **29**, 1222 (1964)) is ~-8. Pritchard and Long (J. G. Pritchard and F. A. Long, *J. Am. Chem. Soc.*, **78**, 2667 (1956)) have found the ρ^* for alkyl epoxides to be 1.95 which yields a ρ_1 of ~12.2. Since ρ_1 is much larger for epoxides than amines, the anticipated change in pK_a is expected to be >2.0.
- D. L. Whalen, J. A. Montemarano, D. R. Thakker, H. Yagi, and D. M. Jerina, *J. Am. Chem. Soc.*, **99**, 5522 (1977).
- P. B. Hulbert, *Nature*, **256**, 5513 (1975).
- Nonnucleophilic neighboring hydroxyl group participation is seen in many hydrolytic reactions (see T. C. Bruice and S. J. Benkovic, "Bioorganic Mechanisms", Vol. 1, W. A. Benjamin, New York, N.Y., 1966, Chapter 1) and has been attributed to assistance in the solvation of the transition state (T. C. Bruice and T. H. Fife, *J. Am. Chem. Soc.*, **84**, 1973 (1962)).
- D. M. Jerina, R. E. Lehr, H. Yagi, O. Hernandez, P. M. Dansette, P. G. Wislocki, A. W. Wood, R. L. Chang, W. Levin, and A. H. Conney in "In Vitro Metabolic Activation in Mutagenesis Testing", F. J. de Serres, J. R. Bend, and R. M. Philpot, Ed., Elsevier, Amsterdam, 1976, pp 179–195.
- D. Jerina, *Arch. Biochem. Biophys.*, **128**, 176 (1968).
- D. R. Thakker, H. Yagi, A. Y. H. Lu, W. Levin, A. H. Conney, and D. M. Jerina, *Proc. Natl. Acad. Sci. U.S.A.*, **73**, 3381 (1976).
- A portion of this work will be submitted by A.R.B. in partial fulfillment of the requirements for the Ph.D.
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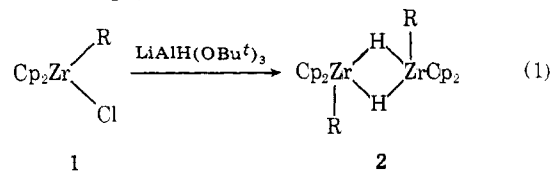
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Hydrogenation of d^0 Complexes: Zirconium(IV) Alkyl Hydrides

Sir:

Catalytic reductive homology of CO in Fischer-Tropsch procedures involves activation of molecular hydrogen. Zirconium(IV) species can reduce^{1,2} or reductively homologate² CO, but Zr(IV)-based systems which function catalytically in this latter role require addition of hydrogen at the hydride oxidation level.² Zirconocene alkyl hydride complexes, $\text{Cp}_2\text{Zr(R)H}$ ($\text{Cp} = \eta^5\text{-C}_5\text{H}_5$), are models for plausible intermediates in the Zr(IV)-catalyzed reductive homology of CO by aluminum hydrides,² and also in Cp_2ZrH_2 -catalyzed hydrogenation of olefins.³ Examination of the possible reaction between H_2 and $\text{Cp}_2\text{Zr(R)H}$ could therefore result in the development of modified CO reduction catalysts which can activate H_2 directly. We find that $\text{Cp}_2\text{Zr(R)H}$ does indeed react with H_2 to afford alkane (R-H) but by an unusual route.

Zirconocene alkyl hydrides (**2**) can be prepared⁴ in yields of ~70% by reaction of $\text{Cp}_2\text{Zr(R)Cl}^5$ (**1**) with $\text{LiAlH}(\text{O}i\text{Bu})_3$ at low temperature (-20°C) in DME, from which they precipitate as white crystalline solids (reaction 1). For example, a solution of 4.55 g (12.7 mmol) **1a** in DME (25 mL), on

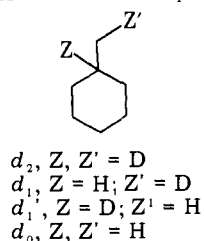
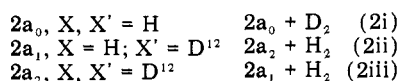
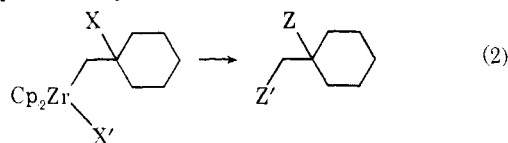


- a, R = (cyclohexyl)methyl
b, R = cyclohexyl
c, R = ethyl
d, R = *n*-octyl
e, R = neopentyl

treatment with 1 equiv of a 1.1 M solution of $\text{LiAlH}(\text{O}i\text{Bu})_3$ in DME, gave **2a** after 8 h at -20°C . The compound, when isolated by filtration and washed with DME and hexane at low

temperature, is sufficiently pure (by NMR analysis) to use without recrystallization, which is, however, possible from toluene at low temperature. Hydrolysis of **2** gives the corresponding alkane (R-H) and hydrogen.⁶ Reaction of **2** with acetone gives $\text{Cp}_2\text{Zr}(\text{R})(\text{OPr}^t)$,⁷ confirming that the Zr-H unit is hydridic. These alkyl hydride compounds are air and moisture sensitive and thermally unstable in solution, though they can be stored indefinitely as solids under N_2 at -30°C . They are moderately soluble in aromatic solvents and ethers but are insoluble in aliphatic hydrocarbons. The broad ($\nu_{1/2} = 4.9$ Hz) resonance at $\tau \sim 12$ in ^1H NMR spectra⁸ of these alkyl hydrides is absent when **2** is prepared from $\text{LiAlD}(\text{O}i\text{Bu})_3$ and is assigned to the hydride ligand. This chemical shift is consistent with that expected for a bridging hydride (Zr-H-Zr) and suggests that these compounds (**2**) are dimeric.^{9,10} Cryoscopic molecular weight determination for **2a** in benzene indicates that it is a dimer which is partially dissociated in solution (for $\text{C}_{34}\text{H}_{48}\text{Zr}_2$, calcd 638, found $568 \pm 10\%$). We propose that reaction of **2** with H_2 occurs through a reactive monomer.

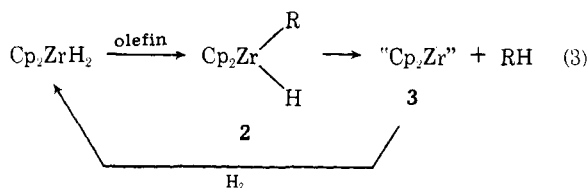
In the absence of H_2 , **2a** decomposed slowly in toluene over a period of several days (at room temperature) to give methylcyclohexane (50–60%). When complex **2a** (0.34 mmol) was stirred in toluene (6 mL) at room temperature under purified H_2 (1 atm), ~ 0.7 equiv of H_2 was absorbed in 3.5 h and methylcyclohexane (70%) and Cp_2ZrH_2 (identified by reaction with acetone to give $\text{Cp}_2\text{Zr}(\text{OPr}^t)_2$ ¹¹) were produced. Hydrogenation of **2** is first order in H_2 ; reaction of **2** with H_2 proceeds approximately five times faster than with D_2 . Ex-



		Reaction		
		2i	2ii	2iii
Methylcyclohexane ^a	d_2	20	5	<1
	d_1	55	15	15
	d_1'	10	75	5
	d_0	15	5	80

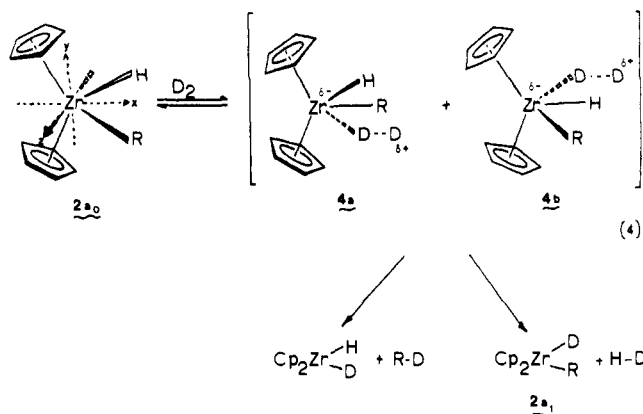
^a Approximate extent of label incorporation in methylcyclohexane determined by GC/mass spectral analysis.¹³

periments using selectively labeled zirconocene alkyl hydride starting materials¹² (see reaction 2) show that most of the methylcyclohexane produced under hydrogen incorporates label from the atmosphere. Methylcyclohexane is formed, therefore, *after* reaction of **2** with hydrogen; a simple scheme (such as shown in reaction 3) involving reductive elimination



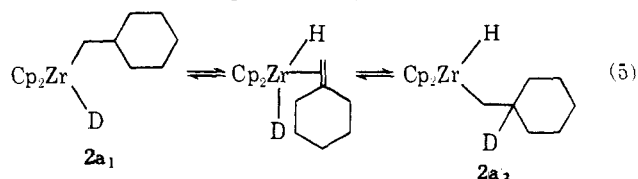
of alkane from **2** followed by oxidative addition of H_2 to "zirconocene" species **3** cannot be operative. Indeed, simple elimination as shown in reaction 3 does not even occur in autodecomposition; for example, **2a** decomposes to a complex mixture of labeled and unlabeled methylcyclohexanes— d_0 , d_1 , and d_2 (irrespective of reaction in toluene or toluene- d_8).

Activation of hydrogen commonly occurs by oxidative addition to a coordinatively unsaturated metal center. Although **2**, a "16-electron" complex, is coordinatively unsaturated, formal oxidative addition to a d^0 Zr(IV) species seems improbable. We propose that these unsaturated Zr(IV) species can react with H_2 directly by hydride abstraction as shown in reaction 4, which is analogous to the reaction of Cp_2ZrH_2 and HAIR_2 .¹⁴ For "bent sandwich" d^0 complexes, the lowest lying vacant orbital has been described.¹⁵ We suggest that H_2 (or

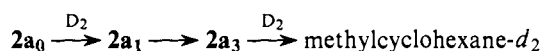


as shown in reaction 4, D_2) reacts with d^0 species **2** by attack involving this vacant orbital, producing 5-coordinate intermediate **4a** or **4b**. Electrophilic attack by H^+ (or, here, D^+) on **4** can give either alkane or labeled zirconium alkyl. This mechanism is substantiated by the observation that scrambling of hydride label with D_2 occurs for **2a** faster than does production of R-D; treatment of **2a** (0.34 mmol) with D_2 (1 atm) at room temperature for 1 h gave 46% deuterium incorporation in the hydride position (monitored by NMR analysis of the acetone-derived isopropoxide); during this time only $\sim 10\%$ R-D had been formed.

We have shown¹⁶ that unsymmetrically labeled compounds **2a** and **2a** are in equilibrium (reaction 5). Formation of



methylcyclohexane- d_2 (in reaction 2i) probably occurs, therefore, through successive label-scrambling procedures:



Hydrogenation of unsaturated d^0 complexes can occur by direct reaction with H_2 and may proceed by a hydride abstraction mechanism. This conclusion may be of general consequence, and the sequence proposed herein can be used to explain other examples of facile hydrogenation of d^0 complexes which have been noted in the literature.^{17,18}

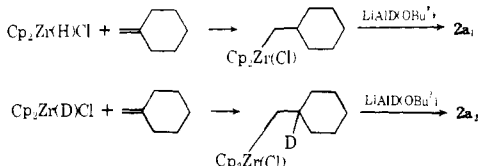
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References and Notes

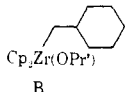
- (1) J. M. Manriquez, D. R. McAllister, R. D. Sanner, and J. E. Bercaw, *J. Am. Chem. Soc.*, **98**, 6733 (1976).
- (2) L. I. Shoer and J. Schwartz, *J. Am. Chem. Soc.*, **99**, 5831 (1977).
- (3) P. C. Wailes, H. Weigold, and A. P. Bell, *J. Organomet. Chem.*, **43**, C32 (1972).
- (4) All reactions were performed under an atmosphere of dry argon. Solvents were dried by distillation from sodium or sodium benzophenone ketyl under nitrogen.
- (5) Compounds **1a-d** were prepared from $\text{Cp}_2\text{Zr}(\text{H})\text{Cl}$ and the corresponding olefin: J. Schwartz and J. A. Labinger, *Angew. Chem., Int. Ed. Engl.*, **15**, 33 (1976). Compound **1e** was prepared from Cp_2ZrCl_2 and neopentyl lithium.
- (6) For example, hydrolysis of crude **2a** with 2 N aqueous H_2SO_4 gave methylcyclohexane (90% by VPC) and H_2 (110% gas buret).
- (7) Identified by ^1H NMR and hydrolysis to yield RH and $^i\text{PrOH}$ (GC/mass spectral identification). For $\text{R} = \text{A}$, ^1H NMR (benzene- d_6) δ 5.73 (10 H, s, Cp), 3.97 (1 H, septet, $J = 6$ Hz, $-\text{OCH}-$), 2.17–0.80 (13 H, br, alkyl group), 0.93 (6 H, d, $J = 6$ Hz, $\text{OCH}(\text{CH}_3)_2$).



- (8) For **2a**, ^1H NMR (THF- d_6 , -30°C) δ 5.82 (10 H, s, Cp), 1.7–0.9 (11 H, br, alkyl group), 0.35 (2 H, br, $\alpha\text{-CH}_2$), -2.35 (1 H, br, hydride).
- (9) A similar chemical shift has been reported for the bridging hydride in [bis(π -tetrahydroindenyl)zirconium dihydride] $_2$ (H. Weigold, A. P. Bell, and R. I. Willing, *J. Organomet. Chem.*, **73**, C23 (1974)) and is inconsistent with that for terminal hydrides in Zr(IV) species.¹
- (10) One member of this series, $\text{Cp}_2\text{Zr}(\text{CH}_3)_2$, is reported to be polymeric and has not been spectrally characterized: P. C. Wailes and H. Weigold, *J. Organomet. Chem.*, **24**, 405 (1970).
- (11) P. C. Wailes and H. Weigold, *J. Organomet. Chem.*, **24**, 413 (1970).
- (12)



- (13) S. Meyerson, T. D. Nevitt, and P. N. Rynalder, *Adv. Mass. Spectrom.*, **2**, 313 (1963). Spectra were also compared with those of authentic deuterated samples.
- (14) L. I. Shoer, K. I. Gell, and J. Schwartz, *J. Organomet. Chem.*, **138**, C19 (1977).
- (15) J. W. Lauher and R. Hoffmann, *J. Am. Chem. Soc.*, **98**, 1729 (1976).
- (16) **2a**, was stirred in dilute toluene solution for 3 h, during which time $\leq 5\%$ methylcyclohexane was formed. Workup of the inorganic product with acetone gave B. The H/D ratio in the α position of the isopropoxide group



was determined as 1.06 by NMR integration. The H/D ratio in the β position of the alkyl group was determined by hydrolysis of the compound with 2 N H_2SO_4 and mass spectral analysis of the resulting methylcyclohexane. The ratio of d_0/d_1 's was ~ 1 .

- (17) Bercaw has proposed Zr(III) intermediates to account for H-D exchange in $(\text{C}_5\text{Me}_5)_2\text{ZrH}_2$: J. E. Bercaw, *Adv. Chem. Ser.*, in press. A similar mechanism is unlikely to explain the exchange of label between the atmosphere and the alkyl hydrides discussed herein.
- (18) K. Clauss and H. Bestian, *Justus Liebigs Ann. Chem.*, **654**, 8 (1962); J. E. Bercaw and H. H. Brintzinger, *J. Am. Chem. Soc.*, **93**, 2045 (1971); P. C. Wailes, H. Weigold, and A. P. Bell, *J. Organomet. Chem.*, **34**, 155 (1972); G. Wilkinson and A. J. Shortland, *J. Chem. Soc., Dalton Trans.*, 872 (1972).
- (19) Alfred P. Sloan Fellow, 1976–.

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Multiphoton Dissociation of Molecules with Low Power Continuous Wave Infrared Laser Radiation

Sir:

It is now a recognized fact that infrared lasers can energize isolated molecules in multiphoton absorption processes.¹⁻³ While vibrational excitation of molecules with CW lasers has

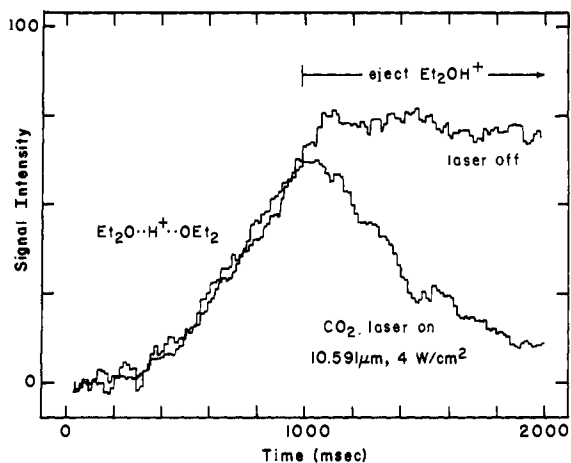


Figure 1. Ion intensity vs. trapping time for a typical multiphoton dissociation experiment. At a diethyl ether pressure of 5.5×10^{-7} Torr ions are formed by a 10-ms 70-eV electron beam pulse. The upper trace is the proton bound dimer signal with the laser off. Ejection of $(\text{C}_2\text{H}_5)_2\text{OH}^+$ beginning at 1-s trapping time halts further formation of the dimer. Continuous irradiation by the infrared laser at 4 W cm^{-2} coincident with ejection of $(\text{C}_2\text{H}_5)_2\text{OH}^+$ (lower trace) results in photodissociation of the dimer. At this pressure the time between collisions is ~ 50 ms.

been used to enhance bimolecular reaction rates⁴ in the gas phase and to effect selective isomerization processes in matrices,⁵ the majority of studies of multiphoton processes have utilized high intensity ($>5 \text{ MW cm}^{-2}$) pulsed CO_2 lasers. Bloembergen and co-workers have recently demonstrated that dissociation probabilities of *isolated* molecules depend only on energy fluence and not on peak laser power.³ Energy fluences used to effect multiphoton dissociation processes have typically been several joules cm^{-2} .³ If it is only energy fluence that is important then there is the intriguing possibility that relatively low power CW lasers (several watts) can effect dissociation processes provided that a molecule can be irradiated under nearly collision free conditions for times approaching 1 s. We wish to report that such conditions can be established and multiphoton dissociation processes are readily observed thus adding a new dimension to this growing field on endeavor.

The experimental methodology is a straightforward application of techniques involving trapped ion cyclotron resonance spectroscopy (ICR)^{6,7} which have been developed and applied to investigate the photochemistry of ions in the gas phase.⁸⁻¹⁴ For the present experiments the output of a line tunable Apollo 550A CW CO_2 laser (bandwidth estimated to be 100 MHz) is directed transverse to the magnetic field through a 92% transparent mesh to irradiate ions in the source region of an ICR cell. The collimated 6-mm-diameter infrared beam is reflected back through the source region by a mirror finish on the bottom plate. Intensity variations across the ion spatial distributions are minimal owing to the small size of the ion packet.¹⁵ Small translations (up to 3 mm) of the laser beam do not alter dissociation rates. A typical experiment thus involves pulsing the electron beam to generate ionic species which can be stored for several seconds, during which time reactions may occur. The ions are then mass analyzed to determine concentrations of the various species present.⁷ The laser can be electronically gated to irradiate ions during any portion of the trapping sequence. Typical neutral pressures are in the range 10^{-7} – 10^{-6} Torr, corresponding to neutral particle densities of 3×10^9 to 3×10^{10} molecules cm^{-3} . Typical ion densities are 10^5 ions cm^{-3} .

The major ions in the 70-eV electron impact mass spectrum of diethyl ether at long trapping times and low pressures are $(\text{C}_2\text{H}_5)_2\text{OH}^+$ and $\text{CH}_3\text{CHOC}_2\text{H}_5^+$.¹⁶ At higher pressures the proton bound dimer is formed in processes 1.¹⁷