with DCPH. An occasional commercial sample of DCPH contained 6–8% of an acidic oxidation product which reacted rapidly with Me_3SnNa. These samples could be purified by simple vacuum distillation under argon.

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Registry No. TBA, 75-64-9; DCPH, 829-84-5; 18-crown-6, 17455-13-9; Me_3SnLi, 17946-71-3; Me_3SnNa, 16643-09-7; Me_3SnK, 72763-68-9; $(n\text{-Bu})_3P$, 998-40-3; MeLi, 917-54-4; Na, 7440-23-5; K, 7440-09-7; $Me_3SnSnMe_3$, 661-69-8; $LSnMe_3$ (L = 3-butenyl), 17314-38-4; $LSnMe_3$ (L = cyclopropylmethyl), 51675-53-7; 1-butene, 106-98-9; methylcyclopropane, 594-11-6; cyclopropylcarbinyl bromide, 7051-34-5; cyclopropylcarbinyl iodide, 33574-02-6.

Interconversion between the Cation Radicals of Toluene and Cycloheptatriene: An Evaluation of the Difference between the Gas Phase and Solution

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The cation radicals of toluene and 1,3,5-cycloheptatriene may be prepared in solution by various means, and the literature in this area offers no evidence for the rearrangement that interconverts these materials in the gas phase. Thermodynamic calculation including estimates for solvation terms suggests a pKa of −12 for these cation radicals. This suggests rapid proton loss, which is consistent with existing measurements. Published theoretical calculations suggest an energy of activation of about 30 kcal mol^{-1} for rearrangement in the gas phase, and this is consistent with lifetime measurements long known in the photodissociation experiments. The information above leads to the conclusion that proton loss from the cation radicals in solution is preemptive of the arrangement. This is contrasted with the McLafferty rearrangement of ketones, which occurs both in the gas and in solution. In this case, proton loss is not a route to stabilization in the cation radicals for unrearranged aliphatic ketones.

In the gas phase, rearrangement attended by scrambling is long known to occur for the dissociating cation radicals of toluene and cycloheptatriene.[1]

In 1959, D. H. Geske electrochemically oxidized 1,3,5-cycloheptatriene in acetonitrile and spectrometrically demonstrated the sole production of tropylium cation.[2] In 1969, W. S. Trahanovsky and co-workers oxidized C-7 monodeuterio-1,3,5-cycloheptatriene with ceric ammonium nitrate in aqueous acetic acid and demonstrated that the deuterium had not scrambled among the six vinyl hydrogens of the cycloheptatriene prior to being lost.[3] These results, which are also consistent with the absence of any product evidence for rearrangement in the literature on oxidation of alkyl aromatics in solution,[4,5] stand in contrast to the gas-phase work.[1] This difference in chemical behavior in the gas phase and in solution is the subject of our current interest.

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(1) (a) The earliest work is reviewed in: H. M. Grubb and S. Meyerson, "Mass Spectroscopy of Organic Ions", F. W. McLafferty, Ed., Academic Press, New York, 1963, p 453 ff. Leading references to the extensive literature: (b) F. W. McLafferty and F. M. Bockhoff, *J. Am. Chem. Soc.*, **101**, 1783 (1979); (c) B. Jane Stapleton, R. D. Bowen, and D. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 1219 (1979); (d) P. Ausloos, *J. Am. Chem. Soc.*, **104**, 5259 (1982); (e) R. C. Dunbar in "Gas Phase Ion Chemistry", M. T. Bowers, Ed., Academic Press, New York, 1979, p 181 ff and, in particular, p 198 ff. (f) The photochemical interconversion of these cation radicals in a frozen argon matrix has been claimed; see B. J. Kesall and L. Andrews, *J. Am. Chem. Soc.*, **105**, 1413 (1983).

(2) D. H. Geske, *J. Am. Chem. Soc.*, **81**, 4145 (1959).

(3) W. S. Trahanovsky, L. B. Young, and M. D. Robbins, *J. Am. Chem. Soc.*, **91**, 7084 (1969). This work shows, as required by the intermediacy of tropylium radical and/or cation, scrambling prior to the second proton (deuteron) loss. Assigning an unlikely isotope effect of unity for each loss yields a *minimum* value of $^3/_1$ d_1/d_0 benzaldehyde for scrambling prior to the first proton (deuteron loss). The experimental result was 1.5/1. We have repeated this experiment in dry HOAc with Co^{III} and obtained benzaldehyde as the major product with d_1/d_0 of 1.1 ± 0.05/1.

(4) There is strong evidence that both oxidizing systems[2,3] proceed via the intermediacy of the cation radical. See L. Eberson, *J. Am. Chem. Soc.*, **105**, 3192 (1983). There is a large literature in metal ion oxidation of toluene, cycloheptatriene, and structurally related materials. Although one-electron oxidations have sometimes been proposed, the evidence outside of Ce^{IV} is controversial. See also: L. Eberson, *Adv. Phys. Org. Chem.*, **18**, 79 (1982).

(5) Consistent with the conclusion on the absence of rearrangement (ref 2 and 3), the solution-phase literature cited below offers no chemical evidence of rearrangement nor, notably, any reference to the gas-phase work where the same cation radicals had exhibited the scrambling rearrangement. For a general review on cation radicals in solution, see, A. J. Bard, A. Ledwith, and H. J. Shine, *Adv. Phys. Org. Chem.*, **13**, 155 (1976). See also: W. S. Trahanovsky and L. B. Young, *J. Chem. Soc.*, **1965**, 5777; *J. Org. Chem.*, **31**, 2033 (1966); L. Syper, *Tetrahedron Lett.* 4493 (1966); K. Sakota, Y. Kamiya, and N. Ohta, *Can. J. Chem.*, **47**, 387 (1969); E. I. Heiba, R. M. Dessa, and W. J. Koehl, Jr., *J. Am. Chem. Soc.*, **91**, 6830 (1969); P. Müller, E. Katten, and J. Rocek, *J. Am. Chem. Soc.*, **93**, 7114 (1971); R. O. C. Norman, C. B. Thomas, and J. S. Willson, *J. Chem. Soc., Perkin Trans 1*, 325 (1973); J. K. Kochi, R. T. Tang, and T. Bernath, *J. Am. Chem. Soc.*, **95**, 7114 (1973); R. Tang and J. K. Kochi, *Inorg. Nucl. Chem.*, **35**, 3845 (1973); R. O. C. Norman, C. B. Thomas, and P. J. Ward, *J. Chem. Soc., Perkin Trans. 1*, 2914 (1973); P. Müller and J. Rocek, *J. Am. Chem. Soc.*, **96**, 2836 (1974); M. E. Kurz and G. W. Hage, *J. Org. Chem.*, **42**, 4080 (1977); E. Baciocchi, L. Mandolini, and C. Rol, *Tetrahedron Lett.* 3343 (1976); L. Eberson and L. Jönsson, *Liebigs Ann. Chem.*, 233 (1977); E. Baciocchi, C. Rol, and L. Mandolini, *J. Org. Chem.*, 42 3682 (1977); A. Bewick, G. J. Edwards, J. M. Mellor, and S. Pons, *J. Chem. Soc., Perkin Trans. 2*, 1952 (1977); P. Müller and T. T. Khoi, *Tetrahedron Lett.* 1939 (1977); K. Nyberg and L.-G. Wistrand, *J. Org. Chem.*, **43**, 2613 (1978); E. Baciocchi, L. Eberson, and C. Rol, *Ibid.*, **47**, 5106 (1982).

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Discussion

A. Solution. Proton loss is an important lifetime limiting event for cation radicals in solution.[6] This suggests that the absence of rearrangement in solution[2-5] could be ascribed to preemptive proton loss.[6] Thermochemical calculations show proton loss to be endothermic by 190 ± 5 kcal/mol^{-1} for the cation radicals of toluene and cycloheptatriene in the gas phase.[7] Reasonable solvation enthalpy estimates for aqueous acetic acid solvent[3] of 50 kcal mol^{-1} for the cation radicals[8] and 8 kcal mol^{-1} for the neutral radicals[9] formed after proton loss combined with the large proton solvation enthalpy (−270 kcal mol^{-1} in H_2O)[10] lead to an expected exothermic proton loss from cycloheptatriene or toluene cation radicals of $\sim$37 kcal mol^{-1} under the conditions of the Ce^{IV} oxidation.[3] This could be reduced to −24 kcal mol^{-1} in acetonitrile[2] because of the lower proton solvation energy in that solvent.[10] A minimum acid strength p*K*a of −17 in aqueous acetic acid can be calculated by allowing an entropy term only for proton solvation.[11] This gives rise to the maximum possible $T\Delta S$ term of +8.6 kcal mol^{-1} at 100 °C, the temperature at which the Ce^{IV} oxidation was conducted.[3] Utilization of the same entropy change, but with a temperature of 25 °C and an exotherm of −24 kcal mol^{-1} yields a p*K*a for the cation radicals of toluene or cycloheptatriene of −12 in acetonitrile. This describes the conditions for the electrochemical oxidation[2] and is in excellent agreement with other methods that estimate the p*K*a of toluene cation radical under these conditions as −10 ± 3.[12]

These materials are obviously strong acids even allowing for considerable variation in the solvation terms above and this suggests rapid, although not diffusion controlled, proton loss.[13,14] The proton loss rate constants in water have been recently measured for a wide range of *n*-methyl-substituted benzene cation radicals including toluene.[13] The rate constants range from 10^7 s^{-1} for toluene cation radical to 10^4 s^{-1} for pentamethylbenzene and show a strong correlation with adiabatic ionization potential. Cycloheptatriene cation radical either from the thermochemical view above or from the ionization potential correlation[15] can be expected to be near to toluene cation radical in its rate constant for proton loss.

B. Gas Phase. In the gas phase those $C_7H_8^{+\cdot}$ species with energy available to fragment by hydrogen atom loss show common characteristics independent of their source and exhibit scrambling.[1] Those $C_7H_8^{+\cdot}$ species with insufficient energy to fragment can be shown to maintain their individual precursor structures for at least a few seconds. These experiments are conducted, allowing for collisions with a neutral gas, to bring the cation radicals to near a thermal distribution at 298 K.[16] The absence of rearrangement in the nondissociating gas-phase cation radicals is consistent with theoretical calculations on the rearrangement which show barriers to rearrangement of greater than 30 kcal mol^{-1} from either toluene or cycloheptatriene cation radicals.[17,18]

C. Comparison between the Dissolved and Gaseous State. The half-life for proton loss from toluene cation radical as measured in aqueous solution is 7×10^{-8} s at 298 K.[15] As discussed above cycloheptatriene cation radical should exhibit a similarly short half-life. These values are a reasonable model for the conditions in the Ce^{IV} oxidation that takes place in an aqueous solvent.[3] Although neither toluene nor cycloheptatriene cation radical proton loss rates have been measured in dry acetonitrile (the solvent of interest for the electrochemical work),[2] the value for hexamethylbenzene is known to be ca. 5×10^2 ($t^{1/2} = 1 \times 10^{-3}$ s) at room temperature.[19] As shown,[15] increased substitution decreases the rate of proton loss and therefore toluene or cycloheptatriene cation radical in dry acetonitrile will have a half-life for proton loss shorter than 10^{-3} s.

As demonstrated above, both experiment[16] and theory[17,18] show the rearrangement of half-life for the gaseous cation radicals of toluene and cycloheptatriene is at least many seconds. We can expect this to be an excellent approximation in the dissolved states[2,3] because the charged radical nature of both species and the transition state(s) between them is a constant structural feature. It follows that it is unreasonable to expect specific solvation to have a large effect on the *relative* energies on the rearrangement surface. This argument is supported by the fact that a structural variety of delocalized carbocations show the same solvation energy in water.[8] It follows that we can expect the rearrangement energy of activation for the cation radicals in solution[2,3] to be similar to that in the gas phase and therefore also attended by half-lives of at least seconds.[16-18] Since the half-life for proton loss from either toluene or cycloheptatriene cation radical is near to 10^{-8} s in aqueous solution and near to 10^{-3} s in acetonitrile (vide supra), it must follow that we can expect the

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(6) See, for example, and leading references: S. F. Nelson, D. J. Steffek, G. T. Cunkle, and P. M. Gannett, *J. Am. Chem. Soc.*, **104**, 6641 (1982).

(7) The necessary heats of formation may be obtained from data in: "Ionization Potentials, Appearance Potentials, and the Heats of Formation of Gaseous Positive Ions", NSRDS, National Bureau of Standards 26, by J. L. Franklin, J. G. Dillard, H. M. Rosenstock, J. T. Herron, K. Draxl, and F. H. Field, Publ. U.S. Government Printing Office, Washington, D. C. 20402, 1969. See ref 1b (Scheme I).

(8) This value has been estimated for water as solvent for similar cyclic delocalized carbocations in the absence of hydrogen bonding. See: J. F. Wolf, P. G. Harch, and R. W. Taft, *J. Am. Chem. Soc.*, **97**, 2904 (1975) and references therein.

(9) The benzyl and cycloheptatrienyl radicals were modeled to neutral counterparts such as benzene and toluene. See: P. P. S. Saluja, T. M. Young, R. F. Rodewald, F. H. Fuchs, D. Kholi, and R. Fuchs, *J. Am. Chem. Soc.*, **99**, 2949 (1977).

(10) The proton solvation energy in a wide variety of polar solvents is known. See: R. Domain, M. Rinfret, and R. L. Benoit, *Can. J. Chem.*, **54**, 2101 (1976) and references therein to earlier literature in this area.

(11) Noyes (R. M. Noyes, *J. Am. Chem. Soc.*, **84**, 513 (1962)) determined the ΔS for proton hydration to be 23 cal deg^{-1} mol^{-1}. The overall ΔS for proton loss must be lower. For discussion of structure and compensating thermodynamic factors on acidity, see: R. P. Bell, "The Proton in Chemistry", 2nd ed., Chapman & Hall, London, 1973, Chapter 6 and p 91 and discussion.

(12) A. M. de P. Nicholas and D. R. Arnold, *Can. J. Chem.*, **60**, 2165 (1982).

(13) See R. P. Bell in ref 11, Chapter 7, for an excellent discussion of this area. For detailed results and discussion see: M. Eigen and L. DeMaeyer, "Technique of Organic Chemistry, Rates and Mechanisms of Reactions", Part II, A. Weissberger, Ed., Wiley-Interscience, New York, 1963.

(14) F. Hibbert in "Comprehensive Chemical Kinetics", Volume 8, C. H. Bamford, C. F. H. Tipper, Eds.; Elsevier, New York, 1977, Chapter 2.

(15) K. Sehested and J. Holoman, *J. Phys. Chem.*, **82**, 651 (1978).

(16) R. C. Dunbar and E. W. Fu, *J. Am. Chem. Soc.*, **95**, 2716 (1973). See also ref 1e herein.

(17) M. J. S. Dewar and D. Landman, *J. Am. Chem. Soc.*, **99**, 2446 (1977). This work suggests that the accepted heat of formation of cycloheptatriene cation radical (ref 7) is too high because there is an unusually large difference between the adiabatic and vertical ionization potentials, following from a large change in geometry in going from the neutral to the ion. This argument exactly parallels one used by others for dimethyl sulfide. See: J. J. Butler, T. Baer, and S. A. Evans, Jr., *J. Am. Chem. Soc.*, **105**, 3451 (1983).

(18) Neutral toluene and cycloheptatriene rearrange with activation parameters: $E = 52.2$ kcal mol^{-1}; $\log A = 13.90$. See S. W. Benson and H. E. O'Neal, "Kinetic Data on Gas Phase Unimolecular Reactions", National Bureau of Standards, NSRDS-NBS 21, 1970, p 318 and references therein. Arrhenius calculation of the rate constant for the cation radicals using the theoretical activation energies (ref 17) and log *A* of 13.90 or even 3 orders of magnitude less shows there will be no observed rearrangement during the lifetimes reported under the conditions in ref 16.

(19) V. D. Parker, *Acta Chem. Scand., Ser. B*, **35**, 123 (1981).

dissolved cation radicals under the conditions of the metal-ion oxidation[3] or the electrochemical oxidation[2] to exhibit proton loss to the preemptive exclusion of rearrangement.

The relationship between the dissolved and gaseous state in the toluene and cycloheptatriene cation radical system stands in contrast to aliphatic ketone cation radicals where McLafferty rearrangement occurs in both states.[20,21] In the latter case, the hydrogen-transfer portion of the overall rearrangement bears a small energy of activation and the charge is localized on oxygen with no stabilization route accessible by proton loss. Interestingly though, after γ-hydrogen transfer of hydrogen to oxygen does open a route to stabilization via proton loss, only the dissolved intermediate can act as a Brønstead acid, thereby avoiding the carbon–carbon bond cleavage encountered in the gaseous state.[21]

Cation radicals are an interesting and increasingly important type of species.[4–6,22] The present work suggests that Brønstead acidity is an important characteristic in evaluating the correspondence between the chemistry in solution and the many observations made on cation radicals in mass spectrometric experiments in the gaseous state.

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Registry No. Toluene cation radical, 34504-47-7; cycloheptatriene cation radical, 34488-67-0.

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[21] D. G. I. Kingston, J. T. Bursey, and M. M. Bursey, *Chem. Rev.*, **74**, 215 (1974).

[22] A recent review with leading references is F. Minisci, A. Citterio, and C. Giordano, *Acc. Chem. Res.*, **16**, 27 (1983).

Notes

Total Synthesis of (±)-Corydalic Acid Methyl Ester

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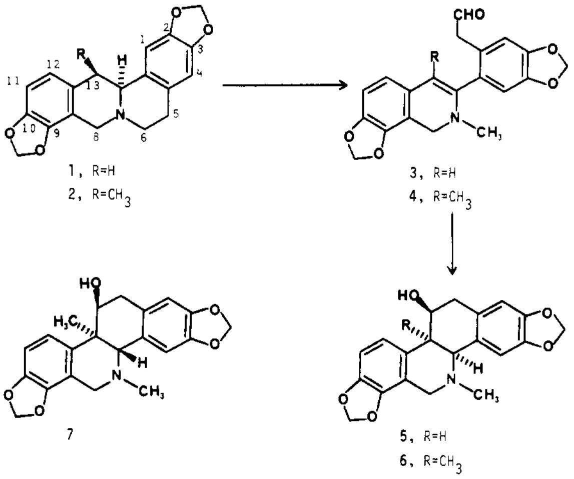
The suggestion that the benzophenanthridine alkaloids [e.g., chelidonine (**5**), corynoline (**6**), and 14-epicorynoline (**7**)] are derived biosynthetically from the tetrahydroprotoberberines [e.g., stylopine (**1**) and tetrahydrocorysamine (**2**)] by an oxidative cleavage of the C-6 to N-7 bond, followed by the joining of C-6 to C-13,[1] has been confirmed experimentally by Leete,[2–4] Battersby,[5–8] Takao,[9,10] Nonaka,[11] and their co-workers. The *B*-secoprotoberberine alkaloid corydalic acid methyl ester (**15**), which has been isolated from *Corydalis incisa*,[12] is presumably derived from the hypothetical intermediate **4** (Scheme I) in this conversion. However, the exact sequence of intermediates involved in the biosynthetic conversion of the tetrahydroprotoberberines to the benzophenanthridine alkaloids remains unclear. The development of methodology that would allow the synthetic incorporation of isotopes into a variety of molecules related to the hypothetical intermediate enamines **3** and **4** could eventually provide labeled compounds for tracer experiments and therefore be valuable for our understanding of exactly how this biosynthetic conversion occurs. With this general problem in mind, the first total synthesis of corydalic acid methyl ester (**15**) has been devised and executed as reported herein (Scheme II). The uncertainty at the outset of this work mainly concerned the stereochemical outcome of the initial condensation reaction of compounds **8** and **9** as well as the stereochemistry of the thermal decarboxylation of the intermediate carboxylic acids **10** and **11**.

Scheme I



The condensation of the anhydride **8** with the Schiff base **9** in acetonitrile at room temperature led to a 1:2

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