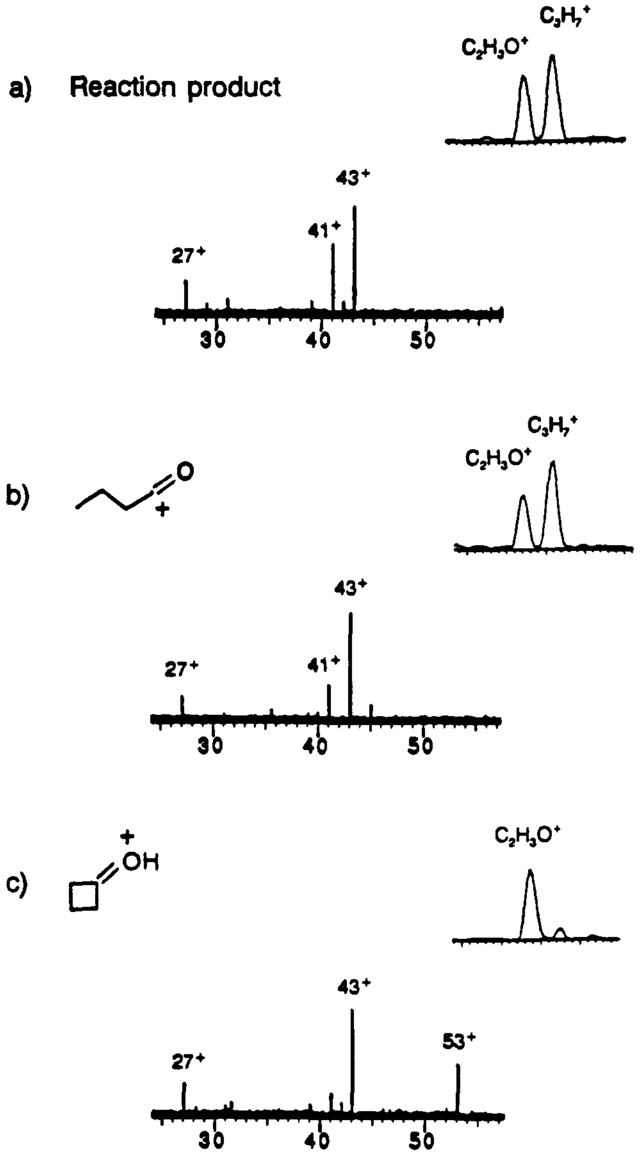

Figure 2. Collision-activated dissociation spectra for (a) ionized cyclobutanone after abstraction of a hydrogen atom from acetone (the reaction product), (b) butanoyl reference ion obtained by loss of a methyl radical from ionized 2-pentanone, and (c) protonated cyclobutanone. The estimated ion kinetic energy is 30–50 eV. Only protonated cyclobutanone loses water to yield a fragment ion of *m/z* 53 upon collisional activation. The insert near each spectrum shows an enlargement of the spectral region at *m/z* 43: the acyclic isomer produces two isobaric ions at this nominal mass value ($C_3H_7^+$ and $C_2H_3O^+$), while the cyclic ion yields predominantly $C_2H_3O^+$.

suggest that only *one* ion structure is involved in the reaction (e.g., linear decay of ionized cyclobutane, Figure 1). If ionized cyclobutanone has an open-chain structure, the barrier for ring opening must be below 17 kcal/mol since the same product distribution is obtained for cyclobutanone ionized by 60-eV electron ionization and by charge exchange with $CS_2^{\bullet+}$ ($\Delta H_{rxn} = -17$ kcal/mol).

In order to address the question concerning the structure of long-lived, ionized cyclobutanone, and thereby the nature of the hydrogen atom abstraction reaction, the structure of the product ion formed in this reaction was investigated. The product ion must have the structure of protonated cyclobutanone if the reactant ion was cyclic (Scheme I). If the reactant, however, had the γ-distonic structure, an acylium ion would be generated upon hydrogen atom abstraction. The dissociation characteristics of two reference ions, obtained by protonating cyclobutanone and by electron-ionization-induced dissociation of 2-pentanone, were investigated. For comparison, ionized cyclobutanone was generated in cell 1 and reacted with acetone in cell 2, as described above. After this, all unwanted ions were ejected from both cells, and the ions of *m/z* 71 were transferred back to cell 1. These ions were then rapidly accelerated to different, predetermined final kinetic energies and allowed to collide with argon (1×10^{-7} Torr) for 100 ms.[13] The product distribution obtained and the energy dependence of the dissociation reactions, were found to be similar to those measured for the acylium reference ion $CH_3CH_2CH_2C{=}O^+$ and different from those measured for protonated cyclobutanone (Figure 2). These results conclusively show that *the reactive form of ionized cyclobutanone is the acyclic γ-distonic ion.* Furthermore, the hydrogen atom abstraction observed for this ion represents the first reported bimolecular reaction wherein a gaseous radical cation undergoes *bond formation at a radical site remote from the charge site.* This and other radical type reactions of distonic ions, including abstraction of a thiomethyl group from dimethyl disulfide by ionized cyclobutanone, will be discussed in detail in a full manuscript.

Acknowledgment. The support provided to this research by the donors of the Petroleum Research Fund, administered by the American Chemical Society, is greatly acknowledged.

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(10) For this estimation, the proton affinity of cyclobutanone is assumed to be equal to that of trimethylene oxide (197 kcal/mol). Note: the proton affinities of cyclopentanone and tetrahydrofuran are the same (198.8 kcal/mol); the proton affinity of cyclohexanone differs by less than 1 kcal/mol from that of tetrahydropyran.[11]

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(12) The heat of formation of $CH_3CH_2CH_2C{=}O^+$ is estimated to be 134 kcal/mol, assuming that the difference in ΔH_f of $CH_3CH_2C{=}O^+$ ($\Delta H_f = 141$ kcal/mol[11]) and $CH_3CH_2CH_2C{=}O^+$ is similar to that between $CH_3CH_2CH_2CH{=}OH^+$ ($\Delta H_f = 124$ kcal/mol[11]) and $CH_3CH_2CH{=}OH^+$ ($\Delta H_f = 131$ kcal/mol[11]). Use of Benson's group additivity procedure gives 136 kcal/mol.

(13) See, for example: (a) Laude, D. A., Jr.; Johlman, C. L.; Brown, R. S.; Wilkins, C. L. *Mass Spectrom. Rev.* **1986**, *5*, 107. (b) Bensimon, M.; Houriet, R. *Int. J. Mass Spectrom. Ion Processes* **1986**, *72*, 93. (c) Forbes, R. A.; Lech, L. M.; Freiser, B. S. *Int. J. Mass Spectrom. Ion Processes* **1987**, *77*, 107. (d) Katritzky, A. R.; Watson, C. H.; Dega-Szafran, Z.; Eyler, J. *J. Am. Chem. Soc.* **1990**, *112*, 2471–2479. (e) Hop, C. E. C. A.; McMahon, T. B.; Willett, G. D. *Int. J. Mass Spectrom. Ion Processes* **1990**, *101*, 191.

Direct Evidence of the Excited-State Intramolecular Proton Transfer in 5-Hydroxyflavone

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One class of the flavonoids, the flavonols, which comprises 3-hydroxyflavone (3HF) and its related compounds, has been applied as a prototype for studying the dynamics of the proton-transfer reaction in the excited state as well as in the ground state.[1,2] To extend the study of the excited-state intramolecular proton transfer (ESIPT) reaction in flavonoids, we have been investigating many natural plant pigments that may show unusual proton-transfer properties. However, naturally occurring flavonoids have a sugar linkage in the 3-position which precludes the ESIPT reaction. On the other hand, approximately 85% of the flavonoids contain an OH group at the 5-position.[3] A prototype example is 5-hydroxyflavone (5HF), which also possesses an in-

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(1) Barbara, P. F.; Walsh, P. K.; Brus, L. E. *J. Phys. Chem.* **1989**, *93*, 29 and references therein.

(2) Chou, P. T.; Martinez, M. L.; Studer, S. L. *J. Am. Chem. Soc.* **1990**, *112*, 2427 and references therein.

(3) *Naturally Occurring Oxygen Ring Compounds*; Dean, F. M., Ed.; Butterworth & Co.: London 1963; pp 280.

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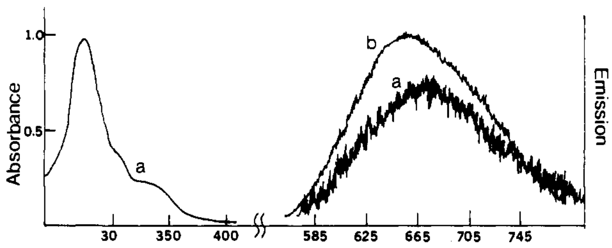


Figure 1. (a) Absorption and emission spectra of 5HF (1.2×10^{-4} M in MCH) at 298 K. (b) The emission spectrum obtained at 77 K. The excitation energy was 2.1 mJ/pulse at 355 nm. The emission spectra were obtained by an average of 100 shots.

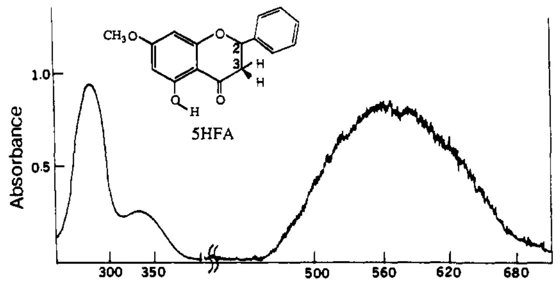
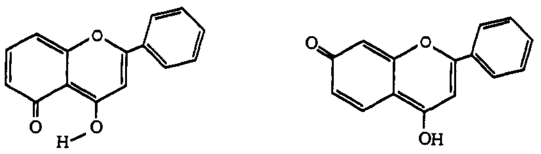


Figure 2. Absorption and emission spectra of 5HFA (5.0×10^{-5} M in MCH) at 298 K.

Scheme I. The Resonance Structures of the Tautomeric Forms of 5HF and 7HF



5HF 7HF

tramolecular H bond. IR data show that the intramolecular H bond is stronger in 5HF than in 3HF.[4] In addition, the large pK_a change between the S_0 and S_1 states for 5HF predicts the occurrence of ESIPT.[5,6] However, the excited-state behavior of 5HF is drastically different from that of 3HF. The absence of fluorescence in 5HF in hydrocarbon solution and glasses at 77 K has been reported by Georgievskii and Rybachenko[7] and Wolfbeis et al.[5,6] as well as several others.[8,9] The only emission observed is a structured phosphorescence in the region of 450–600 nm in alcohol glasses at 77 K in which the intramolecular hydrogen bond is broken by the thermally more stable intermolecularly hydrogen bonded form. This "nonluminescent" behavior is in contrast to other *o*-hydroxy aromatic ESIPT molecules[10] as well as all related hydroxyflavones[5,6] in which the fluorescences are measurable. The central question regarding the origin of the radiationless transition for 5HF has received considerable attention based on steady-state and picosecond transient absorption studies. As a result, several deactivation mechanisms have been proposed.[5,6,8,9] Unfortunately, due to the reported "complete" absence of tautomer fluorescence, the actual relaxation dynamics during a proton-transfer cycle are not known.

In this communication, we report the observation of a unique tautomer emission for 5HF in hydrocarbon solvents. Figure 1 shows the absorption and emission spectra of 5HF in methylcyclohexane (MCH) at room temperature. The maximum of the longest absorption band is ~330 nm, with an absorption extinction coefficient of ~6400 L^{-1} cm^{-1}. Solvent-dependent studies indicate that the 330-nm band is composed of several electronic excited states.[5,6,11] Attempts to observe the emission using commercially available fluorometers have failed. However, when a red-sensitive diode array coupled with laser excitation (the third harmonic, 355 nm, of a Nd:YAG laser) was used, an extremely weak and broad emission with a maximum at ~670 nm was observed. This emission is not quenched by oxygen, and its lifetime is ≪20 ns, which is the limit of the resolution of the intensified detector. The possibility that the observed fluorescence results from an impurity has been ruled out by employing several different methods of purification for 5HF. The intensity of the 670-nm emission is identical for all solutions prepared. Since the emission intensity is linearly proportional to the excitation energy and the prepared 5HF concentration, the possibility of the emission originating from a dimer or excimer of 5HF has also been excluded. Due to the low energy output at 300–400 nm generated from the second harmonic of our existing dye laser, it was not possible to obtain the excitation profile. However, no 670-nm emission was observed when the excitation wavelength was tuned from 500 to 590 nm, the likely absorption region of an impurity. Finally, 5-methoxyflavone (5MF), which is used as a non-proton-transfer model, did not show any fluorescence over the region 500–750 nm. We therefore conclude that the 670-nm emission originates from the $S'_1 \rightarrow S'_0$ (prime indicates the tautomer state) transition. Failure to observe this emission previously may be due to the low emission intensity and unexpected long wavelength. No normal Stokes shifted emission was observed. By comparison of the fluorescence intensity which is integrated over the range of emission frequencies with that of methyl salicylate ($\Phi_f = 0.022$ in cyclohexane[12], a quantum efficiency of the tautomer emission Φ_f of $\sim 3.2 \times 10^{-6}$ was determined for 5HF at 298 K. A temperature-dependent study was also performed. At 77 K the maximum of the tautomer emission is blue-shifted to 658 nm (Figure 1b) with a yield that is ~1 order of magnitude higher than that at 298 K. Upon decreasing the temperature from 77 to 18 K, negligible change in the tautomer emission intensity was observed.

It is noted that, catalyzed by protic solvents, 7-hydroxyflavone (7HF) undergoes excited-state intermolecular proton transfer, giving a tautomer emission with a maximum at 537 nm (in methanol).[13] The 670-nm emission of 5HF, which is ~3690 cm^{-1} lower in energy than that of 7HF, is of surprisingly long wavelength. This can be rationalized by the likely resonance structures for the tautomer species of 7HF and 5HF (Scheme I). For 7HF, the number of π bonds in the conjugated system is four (without counting the phenyl ring). This is comparable to other *o*-hydroxyl aromatic types of ESIPT molecules, resulting in tautomer emission with a maximum generally around 450–560 nm. On the other hand, with one additional π bond in the conjugated system, a smaller energy gap is predicted for the $\pi \rightarrow \pi^*$ transition in 5HF relative to those of typical *o*-hydroxyl aromatic ESIPT molecules. The S'_0–S'_1 energy gap calculated by using the INDO/S method indeed shows a significantly lower energy for 5HF than 7HF.[11] It is most intriguing to compare the tautomer emission of 5HF with that of 5-hydroxy-7-methoxyflavanone (5HFA, Figure 2). In 5HFA the C_2–C_3 double bond in the pyrone ring is hydrogenated, reducing the length of the conjugated system of the tautomer species relative to 5HF. Therefore, the maximum of the tautomer emission is predicted to be similar to those of *o*-hydroxyl aromatic ESIPT molecules. The results depicted in Figure 2 indeed show that the maximum of the tautomer emission of 5HFA is 557 nm,[14] consistent with the proposed conjugation.

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The observation of the 670-nm tautomer emission makes the luminescence study of the mechanism of the radiationless decay for 5HF feasible. Assuming that the thermally activated nonradiative transition is negligible at 18 K, the observed $\Phi \sim 2.3 \times 10^{-5}$ of the tautomer emission for 5HF is indicative of either a negligible yield of the ESIPT or the approximate unit efficiency of the $S'_1 \rightarrow T'_1$ intersystem crossing, resulting in the population of the T'_1 state. For the former case, an ultrafast $S_1 \rightarrow T_1$ intersystem crossing followed by $T_1 \rightarrow T'_1$ proton transfer was proposed by Merritt et al.[14] for the nonluminescent molecule *o*-hydroxybenzophenone. Both mechanisms should result in the population of the T'_1 state. On the basis of the long-wavelength $S'_1 \rightarrow S'_0$ emission, the $T'_1 \rightarrow S'_0$ phosphorescence is predicted to be in the near-infrared region. Therefore, this decay is believed to be dominated by radiationless pathways due to the small T'_1–S'_0 energy gap. Research focused on the dynamics of the triplet state of 5HF is currently in progress.

Registry No. 5HF, 491-78-1.

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(14) Due to the higher sensitivity in the green-red region for the diode array, this 557-nm emission maximum is ~15 nm red shifted in comparison to that measured by using a commercially available fluorometer.

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Total Synthesis of (±)-Kempene-2

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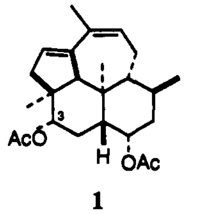
The cembrene-derived tetracyclic diterpenes kempene-1 (**1**), 3-*epi*-**1**, and kempene-2 (**2**) were isolated, along with other terpenes, from the defense secretion of termite soldiers, and their unique structure was determined by NMR studies and X-ray analysis.[1] We now report the first total synthesis of a member of this class of diterpenes. The synthesis of **2** (and therefore the formal synthesis of **1** and 3-*epi*-**1**)[1] utilized Diels–Alder cycloaddition as well as Ti^0-induced dicarbonyl coupling[2] for the formation of the tetracyclic skeleton.



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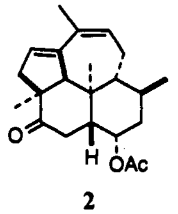
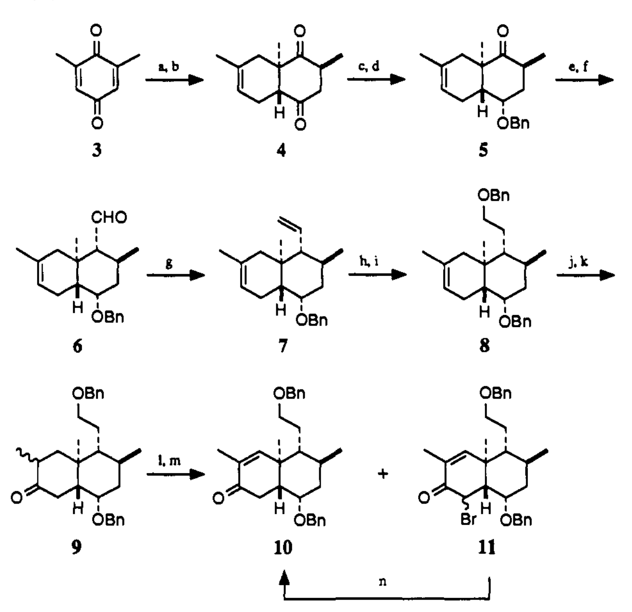


2

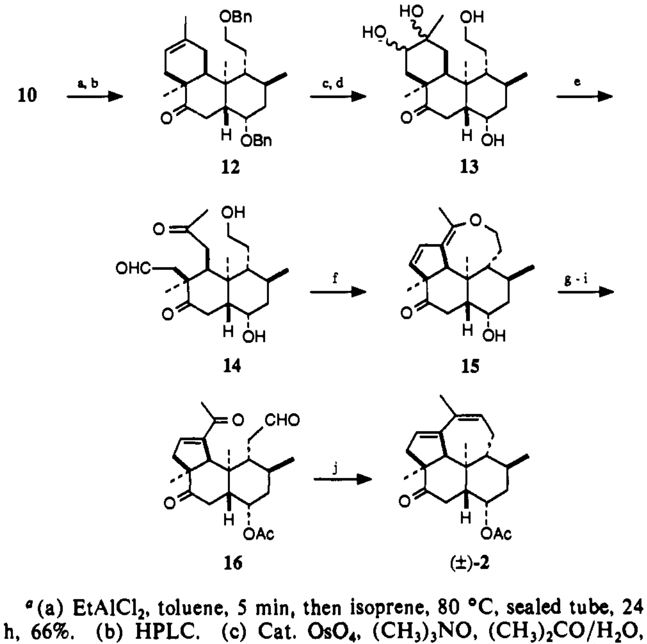
Reaction of 2,6-dimethylbenzoquinone (**3**) with isoprene (Scheme I) in the presence of $BF_3 \cdot Et_2O$ furnished a mixture of regioisomeric *cis*-decalins.[3] The quinone double bond was reduced under equilibrating conditions leading to stereoisomer **4**[4] as the major product, which was further purified by crystallization. LS-Selectride (Aldrich) in cold THF reduced the lesser hindered carbonyl to yield, after normal workup, the axial alcohol as a single isomer, which was converted into its benzyl ether **5**. Introduction of two carbons at the remaining hindered carbonyl function was accomplished by a Peterson type homologation[5] with 1-meth-

Scheme I[a]



[a] (a) $BF_3 \cdot Et_2O$, isoprene, 96 h. (b) Zn, HOAc reflux, 18 h, 13% from **3**. (c) LS-Selectride, THF, −78 °C, then 0 °C, NaOH, H_2O_2, 82%. (d) NaH, BnBr, Bu_4NI, THF, 72 h, 83%. (e) CH_3OCH_2TMS, *sec*-BuLi, THF, −60 °C to −20 °C, 1 h, then **5**, −40 °C, 30 min. (f) HCO_2H, EtOH, 73% from **5**. (g) CH_3PPh_3I, KOtBu, THF, 0 °C, 1 h, then **6**, room temperature, 18 h, 78%. (h) $HB(sia)_2$, THF, 40 °C, 72 h, then 0 °C, NaOH, H_2O_2, 82%. (i) NaH, BnBr, Bu_4NI, THF, 48 h, 98%. (j) $BH_3 \cdot THF$, 0 °C, 6 h, then NaOH, H_2O_2, 77%. (k) $(COCl)_2$, DMSO, CH_2Cl_2, 90%. (l) py·HBr·Br_2, THF, −78 °C, 30 min. (m) LiBr, Li_2CO_3, DMF, 120 °C, 16 h, 60% **10** and 23% **11**. (n) Bu_3SnH, AIBN, C_6H_6, reflux, 24 h, 53%.

Scheme II[a]



[a] (a) $EtAlCl_2$, toluene, 5 min, then isoprene, 80 °C, sealed tube, 24 h, 66%. (b) HPLC. (c) Cat. OsO_4, $(CH_3)_3NO$, $(CH_3)_2CO/H_2O$, 95%. (d) H_2, 10% Pd/C, AcOEt, 88%. (e) $NaIO_4$, dioxane/H_2O, 81%. (f) Cat. $TsOH \cdot H_2O$, C_6H_6, 80 °C, 2 h, 61%. (g) Ac_2O, py, cat. DMAP, 66%. (h) HCl, EtOH, 80 °C, 2 h, 68%. (i) PCC/Al_2O_3, hexane/CH_2Cl_2, 57%. (j) $TiCl_3(DME)_{1.5}$, Zn–Cu, DME, reflux, 4 h, then **16** added over 12 h, 2-h reflux, 32%.

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(3) The ^1H NMR spectrum of the mixture of the cycloadducts as well as the mixture of the initial reduction products showed the presence of a *single* angular methyl group ($\delta \sim 1.2$ ppm), whereas after extended treatment with refluxing acetic acid, the angular methyl group signal appeared at $\delta \sim 0.9$ ppm, indicating the trans ring juncture.

(4) Satisfactory spectral and elemental (±0.4% C, H) or MS-analytical data were obtained for all major compounds listed in the manuscript.

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