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ESR of Transient Radicals during Pyrolysis of Fluids

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Abstract: ESR equipment has been developed for directly observing labile free radicals that are present at high temperatures. A pressurized fluid is heated as it slowly flows through the microwave cavity of the spectrometer. Temperatures to 566 °C and pressures to 140 kg/cm^2 have been used. Radicals are identified from well-resolved hyperfine structure. Spectra of cyanoisopropyl from the decomposition of azobisisobutyronitrile in solution at 155–185 °C and hydroxyisopropyl from 2% di-*tert*-butyl peroxide in isopropyl alcohol at 173–258 °C are reported. Indenyl is reported from indene in benzene at 533 °C and in tetralin at 471 °C. 1,2-Diphenylethyl has been observed from solutions of 1,2-diphenylethane in benzene from 460 to 560 °C. For dilute solutions of 1,2-diphenylethane in toluene the benzyl radical is obtained, while for more concentrated solutions a mixture of radicals is present in the following equilibrium for which $K = 10 \pm 3$ at 560 °C and 105 kg/cm^2: $C_6H_5CH_2CH_2C_6H_5 + C_6H_5\dot{C}H_2 \rightleftarrows C_6H_5\dot{C}HCH_2C_6H_5 + C_6H_5CH_3$. Diphenylmethyl is obtained from the dissociation of tetraphenylethane as a dilute solution in benzene and in 50:50 benzene–diphenylmethane. ESR parameters are given in the latter solvent at 420 °C. The formation of diphenylmethyl from diphenylmethane as a consequence of impurities has been examined, and diphenylmethane that has been initially air oxidized will form diphenylmethyl upon heating. Cumyl is obtained from cumene at 560 °C. α-Methylstyrene is a final product but not dicumyl. Dicumyl in benzene solution at 560 °C decomposes to give disproportionation products cumene and α-methylstyrene. The addition of α-methylstyrene or 1,2-diphenylethane to cumene at 560 °C markedly enhances the production of cumyl. Cumyl is seen from air-saturated cumene at 350 °C. *p*-Cymyl from *p*-cymene, phenylethyl from ethylbenzene containing styrene, and *o*-xylyl from *o*-xylene containing 1,2-diphenylethane have been observed at 560 °C. Hyperfine couplings and *g* values are given and compared with room temperature values, and a discussion involving kinetic parameters is presented.

We have started an electron spin resonance program for the study of free radicals formed in fluids during the course of pyrolysis. Our aim is to obtain a better understanding of the role played by free radicals in high-temperature processes by directly observing these reactive intermediates at steady-state concentration. In this paper, we first describe newly developed techniques and then concentrate largely on the pyrolysis of aromatic hydrocarbons that give rise to benzylic radicals. The substances are of general interest as model compounds in coal-conversion processes and in the combustion of aromatic fuels.

A liquid sample, either the neat compound or a solution, is pressurized and then heated as it slowly flows through the microwave cavity of an ESR spectrometer. The temperature needed to sustain a large enough radical concentration is usually greatly above the critical temperature of the substance used. The reason for pressurizing the system is to maintain a high fluid density. In addition to providing an adequate amount of sample in the microwave cavity, the high density quenches the angular momentum of overall rotation of the radicals. This reduces the ESR line width contribution from the spin-rotational mechanism as described by Schaafsma and Kivelson,[1] who concluded that the contribution varies inversely as the pressure and directly with $T^{3/2}$. A significant finding of this work is that lines at the high pressure are sharp enough to give well-resolved spectra.

Singer and Lewis[2,3] have studied resolved ESR hyperfine structure after pyrolysis of several aromatic hydrocarbons in a silica tube located in the microwave cavity of a spectrometer. Either the neat hydrocarbon or more often a solution in *m*-quinquephenyl (bp 540 °C) was used. The authors point out that "the free radicals must be sufficiently stable so that a reasonably intense EPR signal can be observed. Adequate stable radical concentrations can usually be achieved by thermally quenching the carbonization reactions." In the present work, the spectra of transient radicals were observed with a slowly flowing sample at the pyrolytic temperature. In some cases, the burn-up rate of the sample was so high that a static sample could not have been used. In general, the radicals reported are highly labile, and increased signal strength could usually be achieved by increasing the temperature.

Experimental Section

Essential features of the flow system are shown in Figure 1. The sample was contained in a glass reservoir of 100-mL capacity, and the purging gas, used to remove dissolved oxygen, was helium unless otherwise stated. The high-pressure pump was of the type used for high-pressure liquid chromatography (Waters Model 6000 A) and was normally operated at 1.0 mL/min. Apart from the silica capillary that served as the pyrolysis cell, the tubing of the high-pressure system was 1.59 mm o.d. stainless steel. The silica capillary was 1.4 mm i.d. and 4.7 mm o.d. It connected to the high-pressure stainless steel tubing through seals containing Teflon packing.[4] The rectangular microwave cavity operated in the TE$_{102}$ mode (Varian Model V-4531) and could accommodate objects up to 11 mm in diameter. Pressure transducers were included before and after the pyrolysis cell, and these indicated on chart recorders provided with a scale range of 0–211 kg/cm^2 (0–3000 psi). The cell and seals were statically tested at 280 kg/cm^2, and safety trips for turning the equipment off were set at 211 kg/cm^2. The transducers were calibrated with a precision Bourdon gage supplied by Heise. The throttling valve (Hoke Model 1666 G1Y) was set manually and adjusted as needed during an experiment in order to maintain the desired pressure. The setting of this valve was occasionally troublesome because the flow coefficient (C_v value of 0.0008 fully opened) was larger than ideal. We eventually hope to automate this portion of the equipment. Small-diameter Teflon tubing was used to return liquid from the throttling valve to the reservoir at atmospheric pressure, and, if sufficient gas formed during pyrolysis, it was

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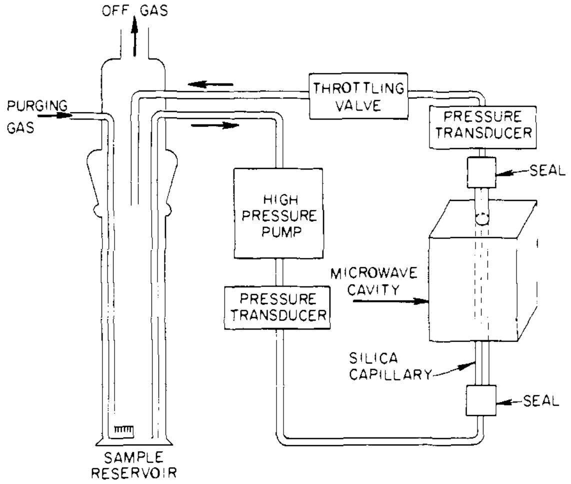


Figure 1. The flow system for pyrolytic studies. The heating arrangement is not shown.

here that bubbles of gas coming out of the solution often could be observed; provision was made for its collection. The total system volume outside of the reservoir was about 15 mL. The samples were recirculated except for a few cases where a larger reservoir of sample was used and the sample discarded as it left the throttling valve.

The heating arrangement is shown in Figure 2. The vacuum jacketed tube was fused silica, and the top portion which traversed the microwave cavity was high-purity silica (Spectrosil) with an outside diameter of 11 mm and inside diameter of 6 mm. The silica capillary was not of high-purity silica, and it did initially give a strong signal, but this signal irreversibly disappeared after operation above 500 °C for a few hours. Air was metered at 30 L/min and passed over an electrically heated coil of Inconel wire (Wilmad heater WG-838 contained within vacuum jacketed silica tube WG-836) and then used to heat the silica capillary. Provision for preventing overheating parts of the system included water cooling on the front face of the cavity, air blown through the cavity, a deflector for preventing hot air from reaching the upper seal, and a stream of air from a small blower directed onto the top seal. A nonmagnetic thermocouple (Type E, chromel–constantan) entered the assembly through the asbestos packing with the tip located just below the interior of the cavity. Temperatures reported here were measured with this thermocouple, which gave the temperature of the heating air and not that of the fluid in the capillary. We made two observations that indicated that the temperature difference between these two locations was not large and did not introduce significant error for the results reported in this paper. One involved the spectrum of phenylhydroxymethyl at 220 °C. The hydroxyl hydrogen hyperfine interaction has a large temperature dependence from which we deduced that the temperature homogeneity of the fluid in the cavity and the offset from the thermocouple reading did not exceed 5 °C. The second was made after threading a fine nickel wire through the capillary and while benzene was circulated at a pressure of 70 kg/cm^2. The ferromagnetic resonance of the nickel was recorded at a number of temperatures through the Curie point (358 °C). Unfortunately, the Curie transition is second order. Bloembergen[5] has shown that the signal can be seen above the Curie point, but it rapidly decreases in intensity. We could follow the signal to 368 °C from which we conclude that the temperature offset must be less than 10 °C. We will eventually obtain a small-diameter thermocouple that can be inserted directly into the capillary. The response of the system to heater current was rapid; heating from room temperature to 560 °C could be achieved in a few minutes. The temperature could easily be held to ±2 °C by manually adjusting the ac heater current. Thus far, we have made observations up to 566 °C, but this is not the upper limit of the equipment. During some experiments a paramagnetic deposit of organic matter collected on the capillary wall. This was removed by flowing 6 N HNO_3 through the capillary at 225 °C and 70 kg/cm^2 for about 30 min.

The spectrometer operated at a nominal frequency of 9.2 GHz and employed 100 kHz magnetic field modulation. A proton resonance probe was located at one side of the cavity, and the proton resonance frequency and the microwave frequency were determined with a frequency counter. Hyperfine values and *g* values including second-order corrections were calculated in the same manner used in previous photolytic studies[6] with an estimated accuracy of ±0.05 G and ±0.000 04, respectively. A correction was needed for the magnetic field difference between the location of the proton resonance probe and the sample. This probe correction was deduced from an accurately measured *g* value for a dilute solution of potassium nitrosodisulfonate (Fremy's salt) on a different spectrometer where the probe correction could be measured directly. The *g* value is 2.005 52 ± 0.000 01 in water solution and also in a solvent of 35% water in isopropyl alcohol. The latter solvent was used in the calibration, since the water solution excessively reduced the *Q* of the cavity of the pyrolytic apparatus.

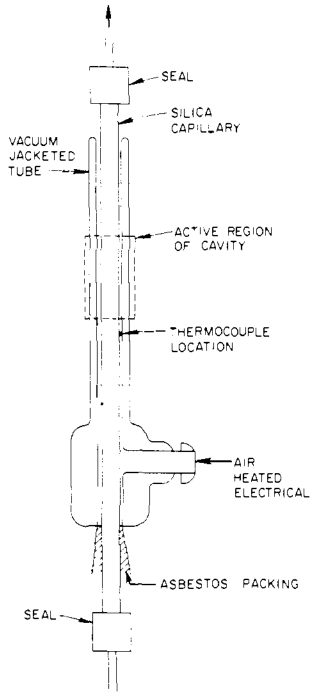


Figure 2. The heating system for pyrolytic studies.

Quantitative assays of spin concentration were made, and 4-hydroxy-2,2,6,6-tetramethylpiperidinyl-1-oxy (purity of over 99% available from Molecular Probes, Inc., as TEMPOL) was used as a standard in a solvent of mixed xylenes. This reference solution was deoxygenated and discarded after passing once through the flow system. DPPH and 4-oxo-2,2,6,6-tetramethylpiperidinyl-1-oxy (TEMPONE) were also tried as reference materials, and, although the results agreed well with the TEMPOL, they were not used, since these substances were found to slowly decompose when they contacted the metal parts of the flow system. Reference and unknown spectra were digitized and stored in a computer memory (Nicolet LAB-80 system), and double integrations were carried out with the computer. The assays are estimated to have an accuracy of 30%.

sym-Tetraphenylethane and 2,3-diphenyl-2,3-dimethylbutane (dicumyl) were obtained from Pfaltz and Bauer. Both were examined by ^1H NMR, and no extraneous proton signals from impurities were found. Other reagents were readily available from commercial sources. All were used as received, and in some cases indicated later additional experiments were done after the reagent was treated with concentrated H_2SO_4 in order to reduce the content of oxidizing impurities and olefinic materials. The procedure was to use successive extractions with concentrated H_2SO_4 until there was no further color change followed by washing with water and a final drying over anhydrous $MgSO_4$.

Results and Discussion

Two systems that pyrolyze easily were examined in the course of developing the equipment. Azobisisobutyronitrile was thermally decomposed, and a well-resolved spectrum of the radical shown in the equation

$$(CH_3)_2C(CN)N{=}NC(CH_3)_2CN \rightarrow N_2 + 2\dot{C}(CH_3)_2CN \quad (1)$$

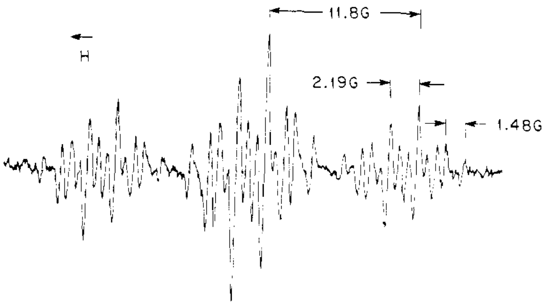


Figure 3. The spectrum from 1.7 M indene in benzene at 533 °C and 70 kg/cm^2.

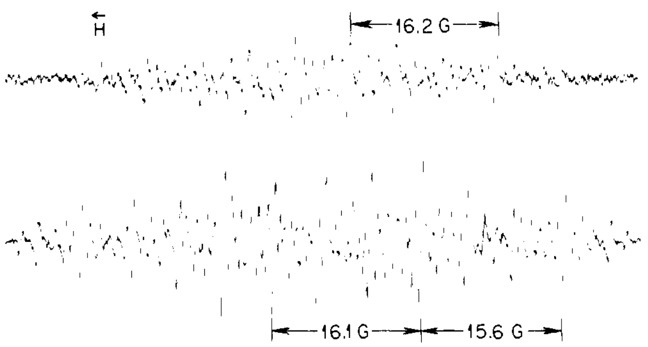
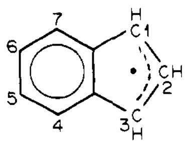


Figure 4. Top: The spectrum of benzyl from 0.3 M 1,2-diphenylethane in toluene at 560 °C and 105 kg/cm^2. Bottom: The spectrum of 1,2-diphenylethyl from 2.2 M 1,2-diphenylethane in benzene at 560 °C and 80 kg/cm^2.

was observed. The spectrum of this radical is known from a room temperature study[7] of the photolysis of isobutyronitrile containing H_2O_2. The spectrum was seen from a 0.17 M solution in dibutyl phthalate at 150 °C and 70 kg/cm^2. Considerable gas attributed to nitrogen was evolved from solution as the sample depressurized at the throttling valve. A well-resolved spectrum was also obtained from a saturated solution of the azo compound in isopropyl alcohol (about 0.04 M) at a pressure of 70 kg/cm^2. In heating above 155 °C, the spectrum became weaker and disappeared at 185 °C. The disappearance is attributed to depletion of the azo compound before the fluid sample reached the interior of the microwave cavity. Here, too, there was a large amount of gas evolution.

A well-resolved spectrum of hydroxyisopropyl, $(CH_3)_2COH$, was observed from the pyrolysis of 2% di-*tert*-butyl peroxide in isopropyl alcohol at a pressure of 70 kg/cm^2. The O–O bond of the peroxide is broken thermally, and the resultant radicals abstract hydrogen from the alcohol. The spectrum is known at room temperature from photolytic studies.[6] In our equipment the spectrum was clearly seen at 173 °C, reached maximum intensity at 220 °C, and vanished upon reaching 258 °C. We attribute the disappearance at the higher temperatures to depletion of the peroxide before the sample arrived in the cavity. After a few hours of operation, the spectrum at 220 °C was noticeably weaker, indicating depletion of the peroxide in the recirculated sample stored in the reservoir.

Indene. Solutions of indene in benzene and in 1,2,3,4-tetrahydronaphthalene (tetralin) were studied. The neat compound was not used for fear that polymerization might foul the system. Benzene by itself did not give a spectrum at temperatures up to 560 °C. Tetralin gave only a weak spectrum at the higher temperatures. The two solutions behaved similarly except that in tetralin a spectrum of given intensity could be obtained at a temperature approximately 60 °C lower. A fairly strong spectrum was present in tetralin at 400 °C, whereas the spectrum just started to appear in benzene at 430 °C. The appearance in benzene at 533 °C with a fresh solution is shown in Figure 3. The spectrum arises from a single radical identified as indenyl (**1**). As pyrolysis continued a central, very broad signal developed which became extremely intense. This signal persisted at room temperature and resulted from a very tenacious coating on the pyrolysis cell which may be largely a polymer of indene. No gas was noted during pyrolysis, but the solution in the reservoir rapidly discolored and soon became very dark.



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Parameters measured for the radical formed from 1.7 M indene in benzene at 533 °C and 70 kg/cm^2 are a *g* value of 2.002 57, a line width of 0.38 G (full width between extremes on the derivative), and hyperfine couplings as follows: $A_{1,3}$, 11.80 G; A_2, 2.19 G; $A_{4,7}$, 2.19 G; $A_{5,6}$, 1.48 G. The values found from 1.7 M indene in tetralin at 471 °C and 70 kg/cm^2 are essentially the same as in benzene solution except for a significantly smaller line width (0.25 G) and a smaller value of $A_{1,3}$ (11.73 G) that is of marginal significance. Hyperfine couplings have been reported[8] for indenyl made by abstracting a hydrogen atom from indene with *tert*-butoxy. This was presumably done photolytically at room temperature. The reported hyperfine couplings are essentially identical with the above except for a slightly different value for $A_{1,3}$ (11.9 G). The assignment of couplings to ring positions had been done with McLachlan calculations which we verified. Indenyl is structurally confined to a plane, and little or no temperature dependence of the hyperfine couplings is expected.

Product analyses show[9] that indene in tetralin at 400 °C is 99% hydrogenated to indan in 1 h. Despite the fact that hydrogenating conditions are present in tetralin solution, we find a radical that is formed by loss of a hydrogen from indene. This radical should be highly stabilized by resonance. In either tetralin or benzene solution, radicals formed by adding a hydrogen atom to the double bond of indene could be present, but their reactivity may be so great that we do not obtain a high enough steady-state concentration to see them.

1,2-Diphenylethane (Bibenzyl). The lower spectrum of Figure 4 was identified as 1,2-diphenylethyl, $C_6H_5\dot{C}HCH_2C_6H_5$, obtained by heating 2.2 M 1,2-diphenylethane in benzene at 560 °C. The spectrum first appeared at 460 °C. At 520 °C there was enough gaseous product to come out of solution after the fluid depressurized at room temperature. The rate of evolution of gas increased to 1.1 mL/min at 560 °C. There were indications of substantial decomposition at 560 °C. Using a recirculation rate of 1.0 mL/min and a total sample volume of 100 mL, the spectral intensity decreased to 70% of its initial value after 135 min, and the sample turned a deep yellow color. A broad, central signal developed which persisted at room temperature. This again was caused by a deposit on the wall of the pyrolytic cell. GC analyses showed formation of a large amount of toluene, a lesser amount of stilbene, and very small amounts of 1,1-diphenylethane and several unidentified products.

The *g* value and hyperfine couplings for 1,2-diphenylethyl are listed in Table I. Resolved splittings were found for hydrogens of only one of the phenyl groups, and these were attributed to the phenyl attached to the carbon with high spin density. The ambiguity in assigning the ortho and meta couplings was easily resolved by comparisons with the values for a variety of substituted benzyl radicals.[10] In a separate experiment, 1,2-diphenylethyl was prepared at room temperature by photolyzing a benzene solution containing 1,2-diphenyl-

Table I. Hyperfine Couplings and *g* Values

radical	*t*, °C	method	hyperfine coupling, G					*g*
			a_o	a_m	a_p	a_α	a_β	
$C_6H_5\dot{C}HCH_2C_6H_5$	560	pyrolysis	4.87	1.85	5.68	16.12	15.56	2.002 59
$C_6H_5\dot{C}HCH_2C_6H_5$	30	photolysis	4.81, 5.08	1.69	5.88	16.13	16.48	2.002 60
$C_6H_5\dot{C}H_2$	560	pyrolysis	5.11	1.96	6.04	16.22		2.002 61
$C_6H_5\dot{C}H_2$	ambient	radiolysis[a]	5.13	1.77	6.17	16.34		2.002 60
$(C_6H_5)_2\dot{C}H$	420	pyrolysis	3.51	1.39	3.94	14.82		2.002 57
$(C_6H_5)_2\dot{C}H$	30	photolysis	3.62	1.33	4.11	14.48		2.002 59
$C_6H_5\dot{C}(CH_3)_2$	560	pyrolysis	4.57	1.77	5.16		16.30	2.002 63
$C_6H_5\dot{C}(CH_3)_2$	30	photolysis	4.74	1.62	5.51		16.23	2.002 62
p-$(CH_3)C_6H_4\dot{C}(CH_3)_2$	560	pyrolysis	4.53	1.77	(CH_3) 5.28		16.09	2.002 65
p-$(CH_3)C_6H_4\dot{C}(CH_3)_2$	30	photolysis	4.74	1.61	(CH_3) 5.77		16.04	2.002 63
$C_6H_5\dot{C}HCH_3$	566	pyrolysis	4.88	1.86	5.68	16.36	17.52	2.002 60
$C_6H_5\dot{C}HCH_3$	30	photolysis[b]	4.81, 5.08	1.69	5.86	16.34	17.63	2.002 62

[a] Reference 10. From toluene in aqueous alkaline solution. [b] Reference 20.

ethane (1.8 M) and benzophenone (0.3 M). The results are given in Table I. The pair of ortho hydrogens appear inequivalent at 30 °C. This is attributed to hindered rotation about the bond from the phenyl group to the α carbon. At 560 °C the rotation rate is much faster, and the pair of ortho hydrogens appear equivalent. The theory of the phenomenon is the same as that used for treating hindered internal rotation in nuclear magnetic resonance.[11] The barrier for rotation arises mainly from overlap of the π electron of the α carbon with the π electrons of the aromatic ring. Coupling constants for hydrogen on α carbons show very little change with temperature, and that is the situation here. The β coupling constant shows a temperature dependence that is not uncommon.[12] An assay of spin concentration with the conditions of Figure 4 (bottom) gave the value 3×10^{-6} M. The line width is 0.37 G. An experiment was carried out in which a portion of the spectrum was examined at pressures of 70 and 140 kg/cm^2. The higher pressure gave approximately a 30% increase in intensity with essentially no change in line width. We attribute the intensity increase to the increased mass of fluid in the active region of the microwave cavity. Since width from spin-rotational coupling varies inversely with the pressure,[1] we believe that the line width does not arise from this interaction. Other concentrations of 1,2-diphenylethane in benzene down to 0.2 M were examined. Apart from intensity, the same spectrum was obtained at all concentrations.

The gas-phase pyrolysis of 1,2-diphenylethane has been studied[13,14] at a variety of temperatures. Based on product analyses the primary step and the major secondary reaction are regarded to be

$$C_6H_5CH_2CH_2C_6H_5 \rightarrow 2C_6H_5\dot{C}H_2 \quad (2)$$

$$C_6H_5\dot{C}H_2 + C_6H_5CH_2CH_2C_6H_5 \rightarrow C_6H_5CH_3 + C_6H_5\dot{C}HCH_2C_6H_5 \quad (3)$$

This mechanism satisfactorily accounts for the 1,2-diphenylethyl that we observe.

The spectrum of benzyl, $C_6H_5\dot{C}H_2$, can be observed during the pyrolysis of 1,2-diphenylethane in the presence of toluene provided that the concentration of toluene is sufficiently high. Pyrolysis of 1,2 diphenylethane in toluene gave much less gaseous products than in benzene. No spectrum is obtained from neat toluene at the temperatures employed. The top spectrum of Figure 4 arises from benzyl obtained by heating 0.32 M 1,2-diphenylethane in toluene at 560 °C. The mole ratio of toluene to 1,2-diphenylethane is 27. This spectrum was obtained using a large volume of solution that was not recirculated. Measured parameters are given in Table I. Parameters are also given for this radical made in a different manner at room temperature. We regard the differences in the parameters at the two temperatures as small and possibly due to radical-solvent interactions. At the higher temperature the density is much less than at room temperature, and strikingly different solvents were used (hydrocarbon for pyrolysis, water for radiolysis). The line width for benzyl in Figure 4 is 0.37 G.

Higher concentrations of 1,2-diphenylethane in toluene gave spectra consisting of a mixture of two radicals, 1,2-diphenylethyl and benzyl. We attribute these findings to the forward and reverse H-abstraction reactions

$$C_6H_5CH_2CH_2C_6H_5 + C_6H_5\dot{C}H_2 \qquad C_6H_5\dot{C}HCH_2C_6H_5 + C_6H_5CH_3 \quad (4)$$

The forward direction is eq 3. Whether a true equilibrium is present depends upon whether the rates are fast compared to rates for the irreversible disappearance of the radicals involved. We have obtained spectra at 560 °C for solutions of 1,2-diphenylethane in toluene with values of the molar ratio of toluene to 1,2-diphenylethane of 15.4, 6.86, and 2.57. Both radicals appear in each solution but at different ratios of radical concentration. A series of computer simulations of spectra was made for a range of radical concentration ratios using the parameters for each radical given in Table I. By matching the simulated and experimental spectra we determined the ratio of radical concentrations from which a value of *K* was calculated:

$$K = \frac{[C_6H_5CH_3]}{[C_6H_5CH_2CH_2C_6H_5]} \frac{[C_6H_5\dot{C}HCH_2C_6H_5]}{[C_6H_5\dot{C}H_2]} \quad (5)$$

Unfortunately, there are only a few small regions of the mixed spectra where the resolution is adequate for conveniently evaluating the ratio of radical concentrations. For molar ratios of toluene to 1,2-diphenylethane of 2.57 and 6.86, we obtained values of *K* of 9.6 and 10.8, respectively. The spectrum with a molar ratio of 15.4 was very weak, and the ratio of radical concentrations was much more poorly deduced. The value of *K* was 7.7. Within our present degree of refinement, it appears that we are measuring a true equilibrium constant, and we report a value of *K* for the equilibrium of 10 ± 3. We intend to make a more detailed study when provision for making better temperature measurements is made. A small amount of the spectrum for 1,2-diphenylethyl is mixed with the benzyl spectrum in Figure 4 (top), but the amount calculated to be present is too small to be seen.

Tetraphenylethane and Diphenylmethane. Strong spectra of diphenylmethyl were obtained by heating dilute solutions of tetraphenylethane. Tetraphenylethane partially dissociates to form diphenylmethyl that presumably is at equilibrium with the tetraphenylethane. The degree of dissociation has not been measured, but it is very small at the temperatures we have employed. Figure 5 shows the spectrum of diphenylmethyl obtained from 0.015 M tetraphenylethane in 50:50 (volume)

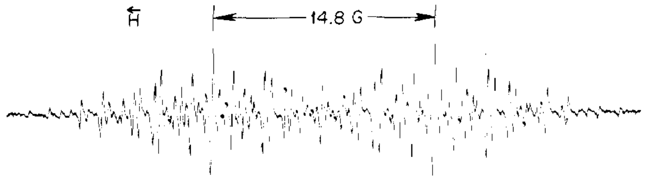

Figure 5. The spectrum of diphenylmethyl from 0.015 M tetraphenylethane in 50:50 (volume) benzene–diphenylmethane at 420 °C and 105 kg/cm^2.

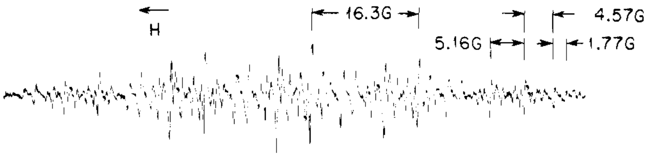

Figure 6. The spectrum of cumyl from cumene at 560 °C and 105 kg/cm^2.

benzene–diphenylmethane at 420 °C and 105 kg/cm^2. Parameters are given in Table I. Values are also listed for this radical prepared photolytically at 30 °C. The solution photolyzed was 25:75 (volume) benzene–diphenylmethane containing a small amount of dicumyl peroxide (0.09 M). Diphenylmethane melts near room temperature, and the benzene prevents crystallization. Hyperfine couplings with somewhat less accuracy have been reported[15] at −40 °C and are in agreement with the values of Table I. Earlier values have also been reported, but it was shown[16] that an error had been made in identification of the radical. The value of a_α (Table I) at 420 °C is noticeably larger than the value at 30 °C, and the values for the ring protons are slightly changed by amounts that are experimentally significant. The temperature dependence might be due to a change in radical–solvent interactions since the density at the higher temperature is greatly reduced. The couplings in this radical are influenced by the angle of twist of the phenyl groups. As the amount of twist becomes larger, there is less delocalization of spin density from the α carbon, resulting in a larger value for a_α and smaller values for the ring coupling constants. Orbital calculations show that the radical is not planar; there is a substantial amount of twist of the phenyl groups.[17] The trend in the couplings in Table I suggests that the amount of twist is somewhat larger at the higher temperature.

The spectrum of diphenylmethyl has also been seen in benzene solution, but it is much weaker. Comparison experiments were carried out with 0.0064 M tetraphenylethane where benzene was the solvent in one case and 50:50 benzene–diphenylmethane in the other case. In both cases the spectra were observed at 430 °C and 70 kg/cm^2, and the line widths were the same. The spectrum with diphenylmethane in the solvent was a factor of 7.4 stronger. This solvent alone gave a spectrum, but it was very weak, only 7% of the intensity obtained with tetraphenylethane present. It is doubtful that higher gas density at 430 °C of the sample with the mixed solvent could account for more than a small part of the factor of 7.4. This indicates that the dissociation of tetraphenylethane may be much greater when diphenylmethane is present, but this is not understood. As discussed below, the role impurities may play is uncertain.

In all of the following experiments, diphenylmethane was present as an equivolume mixture with benzene. Heating of diphenylmethane, as received, gave a spectrum of diphenylmethyl that was seen at 400 °C and became very intense at higher temperatures up to 460 °C. The region above 460 °C was not carefully explored, but in excess of 500 °C the spectrum became weaker. Diphenylmethane (99%) from three commercial sources showed this same general behavior. GC analyses on the starting material showed very weak impurity peaks but no tetraphenylethane. After pyrolysis, a very weak peak identified as tetraphenylethane was present. Diphenylmethane that had been extracted several times with concentrated H_2SO_4, washed, and dried gave a very much weaker spectrum of diphenylmethyl. It is clear that part, if not all, of the spectrum from commercial diphenylmethane is initiated by impurities. It is likely that, after diphenylmethyl is formed, an equilibrium system with tetraphenylethane is established. Gas-phase pyrolytic studies[14] of diphenylmethane showed no decomposition over the temperature range used here; at 700 °C only 2% of the material was converted to products in their apparatus. Diphenylmethane is also reported[9] to be stable in tetralin solution at 400 °C for 18 h.

A number of experiments were carried out in order to understand better the effect of impurities. A strong spectrum of diphenylmethyl was obtained from diphenylmethane (Aldrich, 99%) at 430 °C and 70 kg/cm^2. After treatment with concentrated H_2SO_4 the intensity of the spectrum at 430 °C was approximately 10% of that previously obtained; only the strongest lines were observable. At 460 °C the intensity after treatment with H_2SO_4 was 25% of the former value. Benzophenone is a common impurity in diphenylmethane. The addition of benzophenone to acid-treated diphenylmethane (0.01 and 0.04 M) gave a pronounced enhancement in spectral intensity at 430 °C but not enough to let us attribute all of the observed signal in untreated diphenylmethane to benzophenone.

Dissolved oxygen produces a noticeable effect. At 430 °C the spectrum was not seen if air instead of helium was bubbled through the sample; the sample had dissolved air *during* pyrolysis. In another experiment with diphenylmethane that had been treated with H_2SO_4, the very weak spectral intensity seen previously was first verified at 430 °C. The system was then cooled to room temperature and air instead of helium was bubbled through the sample in the reservoir for 3 h. The system was again purged with helium to remove dissolved oxygen and the spectrum again observed at 430 °C. The spectrum increased noticeably in intensity, more than 100%. Apparently diphenylmethane is readily air oxidized at room temperature to form a product that will initiate diphenylmethyl production upon heating. One possibility is the formation of a hydroperoxide, $(C_6H_5)_2CH(OOH)$. Upon heating we would expect the O–O bond of this compound to break and the resulting radicals to quickly abstract hydrogen from diphenylmethane to give diphenylmethyl. Once diphenylmethyl is formed, its concentration is sustained by equilibrium with tetraphenylethane. We do not know why a spectrum is not seen when air is present during pyrolysis. Possibly the tetraphenylethane that is needed to sustain the spectrum is quickly oxidized.

The strengths of lines of the spectrum of diphenylmethyl show a large, positive temperature dependence. At 420 °C (Figure 5) the line width is approximately 0.16 G. The spectrum is more intense at higher pressures, but the line width stays about the same.

Cumene. The spectrum of cumyl obtained from neat cumene at 560 °C and 105 kg/cm^2 is shown in Figure 6. The radical has six equivalent hydrogens which cause a splitting of the spectrum into seven groups of lines having intensities in the sequence 1:6:15:20:15:6:1. The figure includes all but the 1-strength groups, which were too weak to see. Spectral parameters are given in Table I along with values obtained at 30 °C by photolyzing cumene containing 10% di-*tert*-butyl peroxide. The coupling constants for the ring positions at the two temperatures differ by a somewhat larger amount than in, say, the benzyl radical. Hyperfine couplings for cumyl at −70 °C have been obtained by photolyzing 25% di-*tert*-butyl peroxide in cumene.[18] The quoted accuracy is ±1%. The values generally differ by more than 1% from those at 30 °C in Table I, which may reflect an effect of the lower temperature. The line width in Figure 6 is approximately 0.36 G, and the concentration of cumyl is 1.9×10^{-6} M. At 560 °C there was a moderate amount of gas evolution, approximately 0.5 mL/min. The spectral intensity did not change appreciably upon prolonged heating while the sample was recirculated, and the sample neither discolored nor formed a paramagnetic deposit in the pyrolytic cell.

A number of experiments were carried out to see if the formation of cumyl from cumene is similar to the formation of diphenylmethyl from diphenylmethane. In the latter case, small amounts of impurity initiated radical formation, and the radical concentration was sustained, at least in part, by an equilibrium with the dimer.

Cumene was extracted with concentrated H_2SO_4, washed, and dried, which should lower the concentrations of oxidizing and olefinic impurities. The strengths of the cumyl spectra from this cumene and from untreated cumene at 560 °C were identical. No impurity peaks were found by GC analyses in the treated and untreated cumene before pyrolysis, but, after pyrolysis at 560 °C (100-mL sample recirculated at 1.0 mL/min for 200 min), three weak product peaks were present. Two of the peaks were not identified; the stronger had an area about 2% of the cumene peak. The third peak was identified as α-methylstyrene with an area approximately 1% of the cumene peak. No 2,3-diphenyl-2,3-dimethylbutane (dicumyl) was found. These findings, unlike those in diphenylmethane, show that cumene undergoes slow decomposition at 560 °C and suggest that cumyl formation is not initiated by impurities.

The absence of a GC peak for dicumyl, the symmetric coupling product of cumyl, indicates that this substance does not participate in an equilibrium with cumyl at 560 °C. Further experiments substantiated this view. The spectrum from cumene was observed at 560 °C (Figure 6), and then dicumyl was added (0.008 M) and the spectrum again observed. There was negligible increase in spectral intensity, not over 5%, which indicates that the concentration of cumyl is not sustained by equilibrium with dicumyl. In another experiment, 0.04 M dicumyl in benzene was examined at 450, 500, and 560 °C. At the two highest temperatures the strongest lines from cumyl were at the limit of detection. GC analyses were made on the recirculated product, and in addition to a dicumyl peak there were two stronger peaks identified by preparative GC followed by NMR as cumene and α-methylstyrene. These are the products that are found in the disappearance of cumyl through disproportionation:

$$2C_6H_5\dot{C}(CH_3)_2 \rightarrow C_6H_5CH(CH_3)_2 + C_6H_5(CH_3)C{=}CH_2 \quad (6)$$

The pyrolysis experiment involved 100 mL of solution recirculated at 1.0 mL/min with the pyrolytic cell at a high temperature for 85 min. From the relative strengths of the GC peaks, it was apparent that a major fraction of the dicumyl decomposed in a single pass of the fluid through the hot cell. We conclude that dicumyl is unstable at 560 °C, and in its place appear the disproportionation products cumene and α-methylstyrene.

The effect of adding α-methylstyrene to cumene was examined. At 560 °C the addition of 5% (volume) α-methylstyrene enhanced the cumyl concentration by 50%. It appears that the back reaction of eq 6 may play a role, but the degree of participation was not studied in detail.

Nelsen and Bartlett[19] studied the decomposition of azocumene to form cumyl and the subsequent disappearance of cumyl. At room temperature 94–95% of the cumyl undergoes coupling and 5–6% disproportionation. The coupling product is dicumyl except for an estimated 2% which is a quinoid dicumyl formed by α to para coupling of cumyl radicals. It is thermally unstable at room temperature, dissociating to form cumyl. In benzene solution the ratio of disproportionation to coupling is constant from 20 to 170 °C and dicumyl is stable over this range. In contrast to these results, we find at 560 °C that dicumyl is not a final product and that dicumyl at this temperature decomposes to give the disproportionation products.

Other thermally activated processes were observed in which cumyl was prepared from cumene. A solution of 2 mL of di-*tert*-butyl peroxide in 55 mL of cumene was recirculated at 1.0 mL/min. A very strong spectrum of cumyl was obtained at 230 °C which decayed to 23% of its initial intensity over a 2-h period as the peroxide was depleted. No depletion of peroxide occurred when the solution remained at room temperature for 2 h. It is clear that at 230 °C cumyl disappears irreversibly. The high-field half of the spectrum was noticeably more intense than the low-field half, indicating the presence of dynamic spin polarization. This is the only example of spin polarization seen in the experiments described in this paper. The line width at 230 °C was approximately one-third that found in Figure 6 at 560 °C. In operating the spectrometer, an optimum power level is selected that is high enough to give good spectral intensity but not so high as to unduly broaden the spectrum by saturation. At 230 °C this optimum was approximately 0.5 mW whereas at 560 °C it was 3 mW. The higher power at 560 °C was typical of all radicals observed at this temperature.

If cumene is purged with air instead of helium, a very weak spectrum of cumyl can be obtained as a result of the dissolved oxygen. Upon making repetitive scans of the spectrum at progressively higher temperatures, the cumyl spectrum arising from dissolved oxygen maximized at 350 °C. At 400 °C it had essentially disappeared. We attribute this to depletion of the oxygen before the fluid arrived in the active region of the microwave cavity. At 455 °C the spectrum started to reappear and at 560 °C it regained its full strength as shown in Figure 6. The oxygen probably forms peroxides with subsequent radical initiation in a manner similar to that described for diphenylmethane.

The addition of 1,2-diphenylethane to cumene gives a pronounced enhancement of the concentration of cumyl at 560 °C. The addition of 5 g of 1,2-diphenylethane to 65 mL of cumene increased the spectral intensity of cumyl by 35%. We attribute this to the formation of benzyl from the dissociation of 1,2-diphenylethane which then abstracts hydrogen from cumene. This may be a useful technique for synthesizing many radicals in the region of 560 °C.

***p*-Cymene.** *p*-Cymyl was obtained by heating *p*-cymene. The *p*-cymene was extracted with concentrated H_2SO_4, washed, and dried before use. At 560 °C and 105 kg/cm^2, the spectrum was of comparable intensity to that obtained from cumene (Figure 6), and like cumene there was a moderate amount of gas formation. Parameters for *p*-cymyl at 560 °C are given in Table I along with values at 30 °C obtained by photolyzing *p*-cymene containing about 5% benzophenone. The parameters at the two temperatures are very similar to those of cumyl at the corresponding temperatures, as expected. The *p*-methyl hydrogens of cymyl have approximately the same coupling as the para hydrogen in cumyl. Therefore, the spectrum of *p*-cymyl is very similar in appearance to that of cumyl (Figure 6).

Ethylbenzene. Figure 7 shows a spectrum of $C_6H_5\dot{C}HCH_3$ obtained by heating 0.4 M styrene in ethylbenzene at 560 °C and 105 kg/cm^2. Parameters at 566 °C are given in Table I along with values at 30 °C. The ortho hydrogens are inequivalent at 30 °C. This is another example of hindered internal rotation like that described for 1,2-diphenylethyl. The line width in Figure 7 is 0.38 G.

Ethylbenzene as received showed large effects from impurities. A strong spectrum of $C_6H_5\dot{C}HCH_3$ was obtained at 560 °C. Initially there was heavy gas formation (approxi-

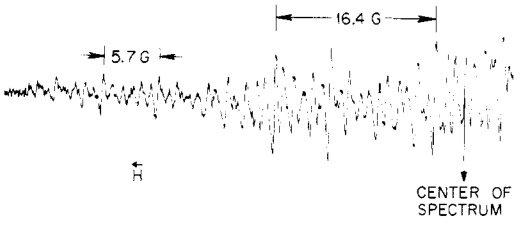

Figure 7. The spectrum of $C_6H_5\dot{C}HCH_3$ from 0.4 M styrene in ethylbenzene at 560 °C and 105 kg/cm^2. A little over one-half of the spectrum which is symmetric about the center is shown.

mately 1 mL/min) which decreased to $\frac{1}{5}$ this value in 2 h, and a very intense, broad signal developed from a deposit in the pyrolysis cell. After extracting ethylbenzene with concentrated H_2SO_4, washing, and drying the signal intensity at 560 °C was only $\frac{1}{3}$ as strong; there was essentially no gas formation and no extraneous signal developed. The concentration of $C_6H_5\dot{C}HCH_3$ increased by 15-20% after 2 h at 560 °C. GC analyses showed a single impurity peak in the H_2SO_4-treated ethylbenzene which increased in intensity by approximately 40% after 2 h at 560 °C. This peak was identified as styrene. The addition of 5% (volume) styrene to H_2SO_4-treated ethylbenzene, the conditions of Figure 7, enhanced the spectral intensity by over 100%. These results indicate that a major pathway at 560 °C for the disappearance of $C_6H_5\dot{C}HCH_3$ is disproportionation, and there may be an equilibrium:

$$2C_6H_5\dot{C}HCH_3 \rightleftarrows C_6H_5CH_2CH_3 + C_6H_5CH{=}CH_2 \tag{7}$$

The formation of $C_6H_5\dot{C}HCH_3$ in these experiments appears to result largely from the presence of styrene. We do not know if the slow growth in radical concentration and styrene content upon prolonged heating is the result of impurities not detected by GC or the result of pyrolysis of ethylbenzene itself.

***o*-Xylene.** The use of 1,2-diphenylethane as a radical initiator proved successful in generating *o*-xylyl from *o*-xylene. A very weak spectrum had been obtained from neat *o*-xylene at 560 °C and 105 kg/cm^2, but it was too weak for analysis. Upon adding 1,2-diphenylethane (0.3 M) a strong spectrum of *o*-xylyl was obtained which was like that reported[20] at 30 °C. Accurate g and hyperfine measurements were not made. The line width was approximately 0.3 G.

Discussion

The experiments that have been described illustrate a new area for the application of electron spin resonance, and it is pertinent to make illustrative calculations relating to experimental parameters and to reaction rates. For the bimolecular disappearance of a free radical with rate constant k the mean lifetime τ may be calculated:

$$-\frac{d[\dot{R}]}{dt} = 2k[\dot{R}]^2 \tag{8}$$

$$\tau = \frac{[\dot{R}]}{-d[\dot{R}]/dt} = \frac{1}{2k[\dot{R}]} \tag{9}$$

A value of k has been reported[21] for cumyl in benzene solution at room temperature, 8×10^9 M^{-1} s^{-1}. The concentration found for cumyl at 560 °C, Figure 6, was 1.9×10^{-6} M. The value of the mean lifetime from eq 9 is 3×10^{-5} s. Rate constants relative to cumyl are reported[21] at room temperature for *p*-cymyl (0.48) and for diphenylmethyl (0.30). From the intensities of the observed spectra, we estimate that the mean lifetimes of these radicals are of the same order of magnitude as for cumyl. The concentration of diphenylmethyl was sustained by equilibrium with tetraphenylethane which was only slightly dissociated.

The density of the sample at the high temperature may be estimated. Of the aromatic substances used, benzene should have the lowest density at 560 °C; it has the lowest molecular weight, and the temperatures employed are well above the critical temperature. The values of critical constants[22] of benzene are 290.5 °C and 50.1 atm. At 560 °C and 105 kg/cm^2 (102 atm), typical operating conditions, the compressibility factor $Z = PV/nRT$ is found from graphical data[23] to be 0.84. This is a moderate departure from an ideal gas ($Z = 1$). The calculated density for gaseous benzene is then 0.14 g/cm^3. The liquid density at room temperature is 0.88 g/cm^3, a factor of 6.3 larger. The gas density of other aromatic compounds generally will be larger because of a larger molecular weight and greater departure from ideality. The values calculated for toluene and ethylbenzene at 560 °C and 105 kg/cm^2 are 0.18 and 0.23 g/cm^3, respectively.

The volume of the pyrolytic cell within the microwave cavity is 0.035 mL. We do not know the temperature gradient along the length of the cell, but when the system is at 560 °C we would expect the volume of fluid undergoing pyrolysis to be somewhat larger, perhaps 0.07 mL. In an experiment with cumene, 100 mL (0.717 mol) was recirculated for 200 min, and 1.9×10^{-6} M cumyl was maintained at steady state. The rate of formation of cumyl, equal to the rate of disappearance in eq 8, is 5.8×10^{-2} M s^{-1}. In the hot region of the pyrolytic cell (0.07 mL) the rate is 4.06×10^{-6} mol s^{-1}, and in 200 min the amount of cumyl formed is 4.9×10^{-2} mol. If all the cumyl disappeared irreversibly and without regeneration of cumene, this would require conversion of 6.8% of the cumene. If the disappearance were exclusively through disproportionation, eq 6, there would be conversion of 3.4% of the cumene to α-methylstyrene. Although these calculations are highly approximate, they illustrate the scale of events taking place. In the cumene system there appeared to be some back reaction when α-methylstyrene was added, and this mechanism would lower the amount of burn-up of cumene required to sustain the radical concentration. During the cumene experiment, gas came out of solution at the rate of approximately 0.5 mL/min. In 200 min the total gas from solution was 4×10^{-3} mol or about 8% of the amount of cumyl formed.

The line width between extremes of the derivative line shape for benzyl and 1,2-diphenylethyl at 560 °C (Figure 4) was 0.37 G. The value found for other radicals at 560 °C was at or near this value. Assuming a Lorentzian line shape, this width corresponds to a spin-spin relaxation time[24] T_2 of 1.8×10^{-7} s. This value sets a limit on the time for a number of processes including a lower limit for the chemical lifetime. Any exchange processes that decorrelate spins do not have lifetimes shorter than this limit. For example, in 1,2-diphenylethyl, the migration of a hydrogen from the β carbon to the α carbon would leave the radical chemically unchanged, but the roles of the two carbons would be interchanged. This process does not proceed with a mean lifetime smaller than 1.8×10^{-7} s. Similarly, in *o*-xylyl the migration of a hydrogen from CH_3 to $\dot{C}H_2$ is not faster than this limit. Consider the reaction of 1,2-diphenylethyl and toluene as given in the equilibrium of eq 4 with rate constant k for the reverse reaction. The mean lifetime of 1,2-diphenylethyl is limited by

$$\tau = \frac{[\dot{R}]}{-d[\dot{R}]/dt} = \frac{1}{k[C_6H_5CH_3]} \geq 1.8 \times 10^{-7} \tag{10}$$

Toluene by itself at 560 °C and 105 kg/cm^2 is 2 M (0.18 g/cm^3). In the experimental study of this equilibrium (eq 4), rather high molar ratios of toluene to 1,2-diphenylethane were used. The concentration of toluene should be somewhat lower than 2 M, but this value should give a reasonable value for the limit. We conclude that for this second-order reaction $k \leq 2.8 \times 10^6$ M^{-1} s^{-1}. From published[25] Arrhenius parameters for the gas-phase abstraction of hydrogen from toluene by methyl, the reaction rate constant at 560 °C is $1.2 \times 10^6\ M^{-1}\ s^{-1}$. We would expect the rate constant with 1,2-diphenylethyl in place of methyl to be smaller. The closeness to the limit suggests that we may find reactions in which line broadening occurs, permitting the measurement of rate constants.

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Synthesis of Prostaglandin H_2†

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Abstract: Prostaglandin H_2 (PGH_2) has been prepared by chemical synthesis from $PGF_{2\alpha}$. The synthesis proceeds from the intermediate $9\beta,11\beta$-dibromo-9,11-dideoxyprostaglandin $F_{2\alpha}$ to the endoperoxide PGH_2 in 17–24% yield upon reaction of the dibromide with silver trifluoroacetate and hydrogen peroxide in diethyl ether. Synthetic PGH_2 was purified by high-pressure liquid chromatography and was characterized by comparison with a biological sample and by conversion to $PGF_{2\alpha}$ methyl ester, PGE_2, and PGH_2 methyl ester under appropriate reaction conditions. Synthetic PGH_2 aggregates human platelet rich plasma that has been preincubated with indomethacin.

Since the two prostaglandin endoperoxides PGG_2 and PGH_2, **1** (Figure 1), were first isolated from incubations of the microsomal fraction of sheep vesicular gland with arachidonic acid,[2] considerable attention has been directed toward developing an understanding of the biochemical mode of action of these unstable species. PGH_2, in particular, lies at a crucial biochemical branch point in the oxidation of arachidonic acid by human platelets. This endoperoxide is converted by platelets to thromboxane A_2, which acts as a potent aggregator of platelets and as a stimulant to vascular smooth muscle.[3] PGH_2, on the other hand, is converted by an enzyme present in vessel walls to PGI_2, an inhibitor of platelet aggregation and a smooth muscle relaxant.[4] The diametrically opposed action of these two intermediates prompted Vane et al. to suggest that they are responsible for the homeostasis of the circulatory system.

Although PGH_2 can be prepared in milligram quantities biologically,[5] preparation of an active cyclooxygenase enzyme is tedious. Further, the enzyme will apparently tolerate very little variation of substrate structure so that the biological preparation of a broad spectrum of analogues has not been possible. Analogues of PGH_2 in which the peroxide linkage (-O-O-) has been replaced by -CH=CH-,[6] -N=N-,[7] $-CH_2O-$,[8] and -S-S-[9] have been chemically synthesized[10,11] and the pharmacology of these analogues has been extensively investigated. Although two syntheses of the methyl ester of PGH_2 have recently been reported[12,13] along with several successful syntheses of simple bicyclic peroxide analogues,[14,15] the parent peroxide, PGH_2, has remained elusive to chemical synthesis. PGH_2 is intrinsically a highly unstable substance ($t_{1/2}$ about 5 min in aqueous solution at 37 °C and pH 7.4) and approaches to its synthesis must utilize mild reaction conditions. In the present paper, we report a chemical synthesis of PGH_2 that proceeds from $PGF_{2\alpha}$ as the starting material. Synthetic PGH_2, purified by high-pressure liquid chromatography, has the full activity of the biological material in platelet aggregation assays.

Experimental Section

Solvents for LC were purified by distillation before use (ethyl acetate from P_2O_5, hexane from sodium). Silver trifluoroacetate was prepared by the method of Janssen and Wilson (see ref 13). H_2O_2 (90%) was obtained as a gift from FMC. LC was carried out on a Waters ALC 202 instrument with a refractive index detector. TLC was carried out on 5 cm × 20 cm × 0.25 mm silica gel plates that were either Merck 60F-254 or Whatman LK5D. ^1H NMR spectra were obtained on a Bruker HFX-90 by FT or CW mode at 0 °C. ^{13}C spectra were obtained in CD_2Cl_2 solvent by the use of a JEOL PS-100 spec-

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† Abbreviations: PG, prostaglandin; LC, high-pressure liquid chromatography; PRP, platelet rich plasma; TLC, thin layer chromatography; TX, thromboxane; HHT, hydroxyheptadienoic acid.

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