(t_r = 6.6 min) and, again, **29** (t_r = 9.5 min). The identity of **21** from this reaction with an authentic sample was confirmed by comparison of the infrared spectra and melting points.

Fluorescence Spectrum of 14a. The emission from a diethyl ether solution, 1.5×10^{-5} *M* in **14a**, was measured with a Cary Model 15 spectrophotometer equipped with a high-powered mercury–Xenon arc lamp and a monochromator adjusted to provide excitation light at 302 nm. A quartz cell was employed, and excitation was perpendicular to the path of the visible light detector of the spectrophotometer.

Synthesis and Photochemistry of Δ^1-4-Alkyltestosterones[1,2]

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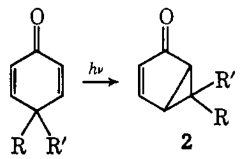
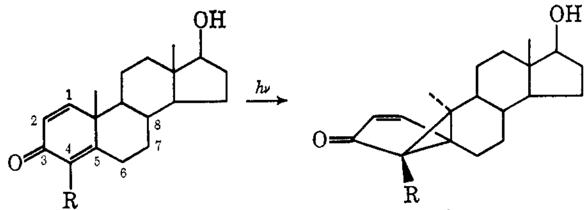
Abstract: The synthesis of several 4-alkylated dehydrotestosterones is described, involving alkylation of testosterone and dehydrogenation using DDQ of the corresponding 17-tetrahydropyranyl ethers. Spectral data for all materials are consistent with the proposed structures. Photolysis of these steroidal dienones at 2537 Å in dioxane gives the corresponding lumiketones, with variable quantum efficiency. Quenching of the reaction is observed with 1,3-cyclohexadiene and *trans*-piperylene, with the efficiency of quenching much greater in all cases with cyclohexadiene. No orderly dependence of the quantum yields or derived rate constants on the size of the alkyl group was observed. Low-temperature absorption and emission studies indicate the lowest triplet in such systems is the π,π^* triplet. It is suggested that the two lowest triplet states, $T_{n,\pi}$ and $T_{\pi,\pi}$, may be in thermal equilibrium at room temperature. It is also postulated that the differential quenching observed with dienes may be due to relaxation of the spectroscopic triplet ($E_T = \sim 70$ kcal/mol) to a triplet ($E_T = \sim 60$ kcal/mol) whose geometry may approximate that of the previously postulated 3,5-bonded intermediate. It is also suggested that inefficiency in these reactions is not due to radiationless decay from the triplet, but rather to return to starting material from some intermediate along the reaction pathway to product.

The photochemical transformation of 2,5-cyclohexadienones **1** into bicyclo[3.1.0]hexenones (lumiketones) **2** has received much attention during the last decade, and the scope and mechanism of the photochemical rearrangement have been elucidated to a considerable extent,[5–9] although some basic questions concerning the nature and lifetime of the reactive excited state are unresolved.[10] One feature of the rearrangement which has not received attention is the role of steric effects on the reaction, as manifested in the quantum yield of the rearrangement and the rate constants for reaction and deactivation of the reactive triplet excited state.

Examination of molecular models indicated that in the course of rearrangement of 4-substituted dehydrotestosterones **3** to the corresponding lumiketones **4**, the R group experiences fairly severe steric interactions with the axial protons at C-6 and C-8. This interference could reduce the rate of product formation from the triplet, relative to the rate of radiationless decay, and might in an extreme situation lead to formation of a new type of product by a reaction path which is usually energetically unfavorable in comparison with the lumirearrangement. Accordingly, a series of compounds of type **3**, with R = H, methyl, ethyl, *n*-butyl, isobutyl, and isoamyl, was synthesized, most of them for the first time, and the details of their photochemistry were investigated.



1 **2**



3 **4**

Results

A. Synthesis of 4-Alkyldehydrotestosterones. Three basic routes to the synthesis of compounds **3** were investigated. The first, based on reactions extensively studied by Stork and his coworkers,[11] involved reductive alkylation of testosterone **5** to 4-substituted di-

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[1] Part XXVII of a series on the photochemistry of unsaturated ketones in solution. XXVI: D. I. Schuster and W. V. Curran, *J. Org. Chem.*, **35**, 4192 (1970).

[2] Supported in part by grants from the U. S. Army Research Office.

[3] Alfred P. Sloan Research Fellow, 1967–1969.

[4] (a) American Cyanamid Junior Educational Award, 1966–1968; (b) this paper is based on the Ph.D. Dissertation of W. C. B., New York University, 1968.

[5] For reviews, see (a) P. J. Kropp, *Org. Photochem.*, **1**, 1 (1967); (b) K. Schaffner, *Advan. Photochem.*, **4**, 81 (1966); H. E. Zimmerman, *ibid.*, **1**, 183 (1963).

[6] H. E. Zimmerman and D. I. Schuster, *J. Amer. Chem. Soc.*, **84**, 4527 (1962).

[7] H. E. Zimmerman and J. S. Swenton, *ibid.*, **89**, 906 (1967).

[8] D. I. Schuster and D. J. Patel, *ibid.*, **90**, 5145 (1968).

[9] J. Frei, C. Ganter, D. Kagi, K. Kocsis, M. Miljkovic, A. Siewinski, R. Wenger, K. Schaffner, and O. Jeger, *Helv. Chim. Acta*, **49**, 1049 (1966).

[10] D. I. Schuster and N. K. Lau, *Mol. Photochem.*, **1**, 415 (1969).

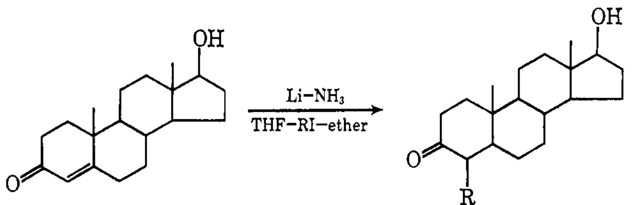
[11] G. Stork, P. Rosen, N. Goldman, R. V. Coombs, and J. Tsuji, *J. Amer. Chem. Soc.*, **87**, 275 (1965).

Table I. Yields and Spectral Properties of 4-Alkyltestosterones **7**

Compd	Mp, °C	Yield, %	λ_{max}, nm[a] (log ϵ)	ν, cm^{-1} [b]	Proton resonances,[c] δ, ppm
7a, R = H			241 (4.21)	1651 1609	18-CH$_3$, 0.79 (s) 19-CH$_3$, 1.19 (s) 17-CH, 3.67 (m) 4-CH, 5.70 (s)
7b, R = CH$_3$	170–172	45	251 (4.18)	1667 1610	18-CH$_3$, 0.80 (s) 19-CH$_3$, 1.19 (s) 4-CH$_3$, 1.78 (s) 17-CH, 3.66 (m)
7c, R = C$_2$H$_5$	139.5–140	41	251 (4.16)	1667 1595	18-CH$_3$, 0.80 (s) 19-CH$_3$, 1.19 (s) 17-CH, 3.65 (m)
7d, R = *n*-C$_4$H$_9$	125–126	56	252 (4.11)	1669 1601	18-CH$_3$, 0.79 (s) 19-CH$_3$, 1.18 (s) 17-CH, 3.65 (m)
7e, R = *i*-C$_4$H$_9$	125–126	35	252 (4.16)	1668 1600	18-CH$_3$, 0.80 (s) 19-CH$_3$, 1.20 (s) 17-CH, 3.65 (m) CH(CH$_3$)$_2$, 0.83 (d), J = 6 Hz
7f, R = *i*-C$_5$H$_{11}$	166–167	57	248 (4.19)	1668 1603	18-CH$_3$, 0.80 (s) 19-CH$_3$, 1.19 (s) 17-CH, 3.66 (m) CH(CH$_3$)$_2$, 0.90 (d), J = 6 Hz
7g, R = CH$_2$CH$_2$Ph	162–164	3.8	252 (4.15)	1668 1601	18-CH$_3$, 0.79 (s) 19-CH$_3$, 1.15 (s) 17-CH, 3.65 (m)

[a] Ultraviolet spectra in methyl alcohol. [b] Infrared spectra in potassium bromide pellet. [c] Nmr spectra in CDCl$_3$ with tetramethylsilane as internal standard.

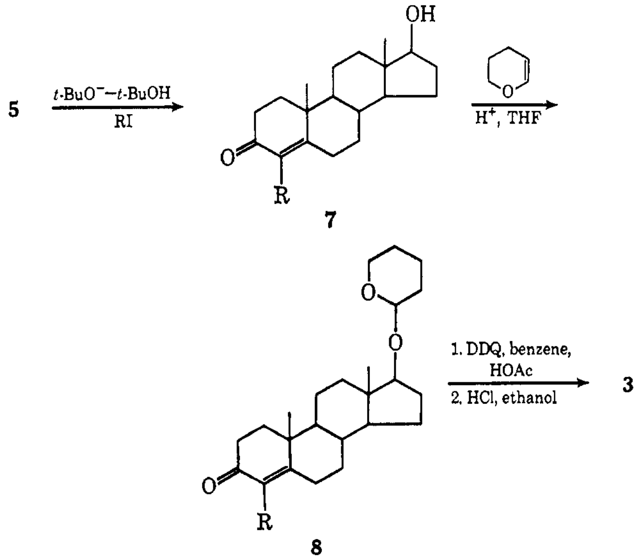
hydrotestosterones **6**, followed by dehydrogenation utilizing 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ) to **3**. By this route, compounds **6** with R = methyl and ethyl were formed in yields of 31 and 3.5%, respectively. The spectral data were consistent with the assigned structures, and for **6**, R = CH$_3$, were identical with those of an authentic sample. Repeated attempts at reductive butylation or hexylation of testosterone resulted only in the formation of 4,5-dihydrotestosterone (**6**, R = H).



5 **6**

The second route investigated, which proved far more successful, is outlined in Chart I. Using the method of Atwater,[12a] reaction of **5** with potassium *tert*-butoxide in hot *tert*-butyl alcohol, followed by reaction with the desired alkyl iodide, gave the desired 4-alkyltestosterones, **7**. The yields in each case, and spectral data for the isolated compounds **7**, are summarized in Table I.[12b] Melting points and ir and uv data for **7b**, **7c**, and **7d** agree well with literature values.[12] The 4,4-dialkylated product was a by-product in all reactions, the amount decreasing as the size of R increased. The β-phenylethyl derivative **7g** was formed in very small yield, precluding further work with this compound. In this case, testosterone was recovered in 83% yield. Dehydrogenation of compounds **7** directly with DDQ gave a mixture of compounds featuring a new carbonyl band at 1740 cm^{-1}, indicating formation of 17-keto derivatives. Because of this, a more circuitous but more productive route to compound **3** was taken involving protection of the 17-hydroxyl group as the 17-tetrahydropyranyl (THP) ether **8**, formed in 80–90% yield by a procedure of Brownfield.[13] Dehydrogenation of **8** with DDQ gave **9** (not isolated), which on hydrolysis

Chart I



a, R = H
b, R = CH$_3$
c, R = C$_2$H$_5$
d, R = *n*-C$_4$H$_9$
e, R = *i*-C$_4$H$_9$
f, R = *i*-C$_5$H$_{11}$

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(12) (a) N. W. Atwater, *J. Amer. Chem. Soc.*, **82**, 2847 (1960). (b) Analytical data for all new compounds can be found in ref 4b.

(13) R. Brownfield, Lederle Laboratories, unpublished work.

Table II. Yields and Spectral Properties of Δ^1-4-Alkyltestosterones **3**

Compd	Mp, °C	Yield, %[a]	λ_{max}, nm[b] (log ϵ)	ν, cm^{-1} [c]	Proton resonances[d] δ, ppm
3a, R = H			244	1667	18-CH_3, 0.83 (s)
			(4.19)	1625	19-CH_3, 1.26 (s)
				1601	2-H, 4-H, 6.23 (m)
				1417	1-H, 7.11 (d), J = 10 Hz
3b, R = CH_3	187–189	43	243	1661	18-CH_3, 0.82 (s)
			(4.05)	1618	19-CH_3, 1.23 (s)
				1601	4-CH_3, 1.90 (s)
				1406	2-H, 6.23 (d), J = 10 Hz
					1-H, 7.05 (d), J = 10 Hz
3c, R = C_2H_5	150–151	25	243	1657	18-CH_3, 0.93 (s)
			(4.05)	1621	19-CH_3, 1.33 (s)
				1601	2-H, 6.32 (d), J = 10 Hz
				1406	1-H, 7.14 (d), J = 10 Hz
3d, R = n-C_4H_9	132–133	35	243	1651	18-CH_3, 0.82 (s)
			(4.04)	1618	19-CH_3, 1.22 (s)
				1596	2-H, 6.20 (d), J = 10 Hz
				1406	1-H, 7.01 (d), J = 10 Hz
3e, R = i-C_4H_9	179–180	32	243	1656	18-CH_3, 0.82 (s)
			(4.06)	1626	19-CH_3, 1.24 (s)
				1598	2-H, 6.23 (d), J = 10 Hz
				1406	1-H, 7.04 (d), J = 10 Hz
					$CH(CH_3)_2$, 0.85 (d), J = 6 Hz
3f, R = i-C_5H_{11}	150–151	36	243	1652	18-CH_3, 0.82 (s)
			(4.06)	1623	19-CH_3, 1.21 (s)
				1601	2-H, 6.21 (d), J = 10 Hz
				1406	1-H, 7.03 (d), J = 10 Hz
					$CH(CH_3)_2$, 0.91 (d), J = 6 Hz

[a] Yields of **7** → **3**. [b] Ultraviolet spectra in methyl alcohol. [c] Infrared spectra in potassium bromide pellet. [d] Nmr spectra in $CDCl_3$, with tetramethylsilane as internal standard.

with HCl in ethanol gave **3**. Optimal yields on the dehydrogenation were found with the ratio steroid: DDQ of 1:2, with overall yields (Table II) of **7** → **3** of 20–40% depending on the substituent. Some **7** was always recovered, even with higher proportions of DDQ, and separation of **7** and **3** required in some cases two or three passes on a silica gel column. The spectral data for compounds **3a**–**3f** are given in Table II. All compounds gave satisfactory elemental analyses,[12b] and the melting point and spectral data for **3b** agreed with literature values.[14] Compounds **3c**–**3f** are apparently new compounds. The spectral data for all compounds **3** are almost identical (Table II) except for those differences expected for the different alkyl substituents, and are exactly what one would expect[9] for such compounds.

A third possible route for synthesis of alkyl-substituted compounds **3** involves direct alkylation of dehydrotestosterone **3a** by the Atwater procedure.[12] In a small-scale reaction, the 4-ethyldienone **3c** was obtained from **3a** in 13% yield, and the product was identical with that obtained from the route described above. It seems likely that this method could be developed into a viable synthesis of substituted dehydrotestosterones and related compounds, although it was not investigated further in this study.

B. Photolysis of 4-Alkyldehydrotestosterones. a. Products. The compounds **3** were photolyzed in dioxane solution at 2537 Å using a Hanau low-pressure NK 6/20 lamp. The reactions were monitored using gas–liquid partition chromatography (glpc). Only a single new peak appeared in the chromatogram. Other materials are undoubtedly formed, as the product peak decreased in size late in the reaction. The yield of product was maximized after 75–80% consumption of starting materials, which required 5–13 hr, depending on the reactant. The product was isolated by column chromatography on alumina. Yields and spectral data for the isolated products are given in Table III.[12b] The melting points and spectral data for **4a** and **4b** agree well with those in the literature.[9,14] The close similarity of the data for **4c**–**4f** with the data for **4a** and **4b** and other known lumiketones[9,14] leaves no doubt that they are the expected bicyclo[3.1.0]hexenones. Some instability of the lumiketones was noted on heating and on standing for long periods of time at room temperature. A number of control experiments, involving in part trimethylsilylation of dienone and lumiketones, and glpc analysis of both silylated and unsilylated ketones at different temperatures, ensured that the glpc analysis for the lumiketone under the conditions used was quantitative. This was of particular importance in the quantum yield and quenching studies (see below).

b. Quantum Yields. Quantum yields for formation of lumiketones **4** in dioxane at 254 ± 10 nm were measured directly using a Bausch & Lomb high-intensity grating monochromator and ferrioxalate actinometry.[15] The analysis for lumiketones was made quantitatively by glpc using tetracosane as internal standard. Conversions of starting material were kept below 10% to ensure that the dienones absorbed at least 95% of the incident light. The data are given in Table IV.

c. Quenching Studies. Quenching of the conversion of **3** → **4** by *trans*-piperylene and 1,3-cyclohexadiene was observed. Competitive irradiation of dioxane so-

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(14) F. Sondheimer and Y. Mazur, *J. Amer. Chem. Soc.*, **79**, 2906 (1957); K. Weinberg, E. C. Utzinger, D. Arigoni, and O. Jeger, *Helv. Chim. Acta*, **43**, 236 (1960).

(15) C. G. Hatchard and C. A. Parker, *Proc. Roy. Soc., Ser. A*, **235**, 518 (1956).

Table III. Yields and Spectral Data of Lumi-Δ^1-4-alkyltestosterones **4**

Compd	Mp, °C	Yield,[a] %	λ_{max}, nm[b] (log ϵ)	ν, cm^{-1} [c]	Proton resonances[d] δ, ppm
4a, R = H		53	237 (3.74)	1690 1567	18-CH_3, 0.76 (s) 19-CH_3, 1.21 (s) 2-H, 5.86 (2d), $J_{1,2}$ = 1 Hz, $J_{2,4}$ = 5.5 Hz 1-H, 7.22 (2d), $J_{1,4}$ = 0.75 Hz
4b, R = CH_3	208–210 164–165[e]	69	246 (3.63)	1684 1568	18-CH_3, 0.76 (s) 19-CH_3, 1.11 (s) 4-CH_3, 1.37 (s) 2-H, 5.80 (d), J = 5.5 Hz 1-H, 7.31 (d), J = 5.5 Hz
4c, R = C_2H_5		56	248 (3.70)	1679 1562	18-CH_3, 0.81 (s) 19-CH_3, 1.11 (s) 2-H, 5.90 (d), J = 5.5 Hz 1-H, 7.38 (d), J = 5.5 Hz
4d, R = n-C_4H_9	123–124[e]	55	248 (3.60)	1695 1568	18-CH_3, 0.78 (s) 19-CH_3, 1.07 (s) 2-H, 5.83 (d), J = 5.5 Hz 1-H, 7.32 (d), J = 5.5 Hz
4e, R = i-C_4H_9		67	248 (3.70)	1685 1568	18-CH_3, 0.79 (s) 19-CH_3, 1.08 (s) 2-H, 5.90 (d), J = 5.5 Hz 1-H, 7.31 (d), J = 5.5 Hz
4f, R = i-C_5H_{11}		73	247 (3.63)	1691 1568	18-CH_3, 0.80 (s) 19-CH_3, 1.08 (s) 2-H, 5.92 (d), J = 5.5 Hz 1-H, 7.32 (d), J = 5.5 Hz

[a] Isolated product yields. [b] Ultraviolet spectra in methyl alcohol. [c] Infrared spectra in potassium bromide pellets. [d] Nmr spectra in $CDCl_3$, tetramethylsilane as internal standard. [e] Melting point of 17-acetate.

Table IV. Quantum Yields, Quenching Data, and Rate Constants

Compd	R	Φ_0[a]	$k_q\tau_0$[b]	$k_q'\tau_0$[c]	k_q/k_q'	$\alpha\tau_0$,[d] sec $\times 10^{10}$	k_r/α,[e] sec^{-1} $\times 10^{-9}$	k_d/α,[e] sec^{-1} $\times 10^{-9}$	$k_r = (\alpha\tau_0)^{-1}$,[f] sec^{-1} $\times 10^9$
3a	H	0.58	2.31 ± 0.16	0.80 ± 0.02	2.9	3.8	1.5	1.1	2.6
3b	Methyl	0.55	0.71 ± 0.02	0.075 ± 0.004	9.5	1.2	4.6	3.7	8.3
3c	Ethyl	0.23	0.29 ± 0.01	0.019 ± 0.001	15.3	0.5	4.6	15.4	20.7
3d	n-Butyl	0.63	0.59 ± 0.04	0.048 ± 0.003	12.5	1.0	6.3	3.7	10.2
3e	Isobutyl	0.37	0.29 ± 0.01	0.021 ± 0.002	13.8	0.5	7.4	12.6	20.7
3f	Isoamyl	0.23	0.32 ± 0.02	0.031 ± 0.006	10.6	0.5	4.6	15.4	18.7

[a] Average of duplicate determinations of product yield at 254 ± 10 nm. [b] Stern–Volmer slope for quenching by 1,3-cyclohexadiene. [c] Stern–Volmer slope for quenching by *trans*-piperylene. [d] $k_q\tau_0/k_{dif}$. See text. [e] Assuming inefficiency is due to radiationless decay from triplet. [f] Assuming no radiationless decay from triplet. See text.

lutions (high-pressure Hg lamp, Pyrex filter) of **3** containing varying amounts of quencher was done in a rotating turntable apparatus ("merry-go-round"),[16] in a bath maintained at 34 ± 1°. Quantitative glpc analysis for lumiketones using internal standards allowed construction of Stern–Volmer plots for each dienone **3** and both quenchers. Excellent straight-line plots were found in all but one case (*vide infra*) and slopes were calculated by computer by the method of least squares, and are given together with the standard deviation in Table IV. At least five different cyclohexadiene concentrations (usually up to 1.0 *M*) and six *trans*-piperylene concentrations (up to 10.0 *M*) were used in each kinetic run. A representative plot, for the case of **3e** → **4e**, is given in Figure 1. Repeat runs were made in several but not all cases, and the slopes of the Stern–Volmer plots were reproducible within the given experimental error, which usually was less than 5%. For detailed data, see ref 4b.

In terms of the rate constants for reaction (k_r) and radiationless decay (k_d) of the triplet excited states, expressions for the triplet lifetime, τ_0, and quantum yield, Φ_0, are given in eq 1 and 2, assuming the efficiency of formation of the triplet is unity.

$$\tau_0 = (k_r + k_d)^{-1} \qquad (1)$$

$$\Phi_0 = k_r(k_r + k_d)^{-1} = k_r\tau_0 \qquad (2)$$

The Stern–Volmer relationship, eq 3, is given in

$$\Phi_0/\Phi = 1 + k_q\tau_0[Q] \qquad (3)$$

terms of the rate constant for energy transfer, k_q. Obviously, energy transfer to piperylene (rate k_q') is not occurring at the diffusion-controlled rate, and there is no assurance that quenching by cyclohexadiene (rate k_q) is diffusion controlled.[17] Therefore, the Stern–Volmer slopes are given by eq 4 in terms of the rate

$$\text{slope} = k_q\tau_0 = \alpha k_{dif}\tau_0 \qquad (4)$$

constant for diffusion,[18] k_{dif}, and the constant α, where α

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(16) F. G. Moses, R. S. H. Liu, and B. M. Monroe, *Mol. Photochem.*, **1**, 245 (1969).

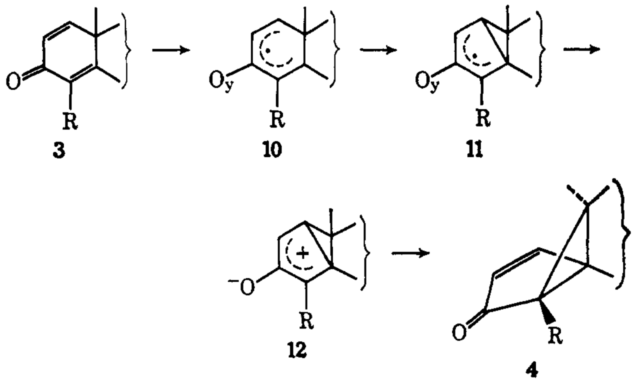
(17) For a study of quenching of two cyclohexadienone triplets by a series of dienes, see ref 10.

(18) A. A. Lamola, "Energy Transfer and Organic Photochemistry," Interscience, New York, N. Y., 1969, p 34.

is the probability that energy transfer occurs during the lifetime of a solution encounter between the dienone triplet and the quencher.[19,20] Such selectivity in energy transfer has been observed for other 2,5-cyclohexadienones.[20] From the quantum yield and cyclohexadiene quenching data, assuming[18] in dioxane $k_{dif} = 6.0 \times 10^9$ l. mol^{-1} sec^{-1}, values of k_r/α and k_d/α can be calculated and are given in Table IV.

Upward curvature of the Stern-Volmer plot for **3b** and 1,3-cyclohexadiene was observed, but at much higher quencher concentrations (>4 *M*) than expected (~0.1 *M*) if $k_q = k_{dif}$.[19]

Chart II



Discussion

There does not appear to be a simple correlation between the quantum yield and quenching data (Table IV) and the steric properties of the substituent at C-4 in these dehydrotestosterones. Since quantum yields are not direct measures of reactivity, it is necessary to correlate structure with rate constants for the specific reactions involved. However, no trend is apparent in the rate constants k_r and k_d in Table IV, assuming a constant value of α in the series,[19] except that both parameters for the unsubstituted compound **3a** are measurably smaller than for the substituted compounds.

The mechanism for the dienone-lumiketone rearrangement, as originally postulated by Zimmerman and Schuster,[6] is summarized in Chart II. Although the intermediacy of zwitterions **12** in these reactions seems to be generally accepted,[5-7,9] this aspect of the mechanism has been questioned recently.[8,21] It has been pointed out[8] that no compelling evidence has been obtained in studies of such reactions in nonpolar solvents which *requires* the intermediacy of zwitterions.[21a] While spin inversion must occur at some stage between the triplet **10** and the product in its ground state,[21] it is possible that spin inversion occurs concomitantly with the final sigmatropic rearrangement of order [1,4],[8] and that the zwitterion **12** does not represent a potential minimum on the energy surface.[21a] Apropos, Zimmerman and Jones[22] have recently reported a study of a cyclohexadienone **13** which is constrained from rearrangement to a lumiketone. There should be no difficulty in forming the zwitterion **14** from **13**, yet attempts to trap such a species with appropriate reagents were unsuccessful.[22] Zimmerman and Jones conclude[22] that rearrangement of cyclohexadienones and decay back to starting material are coupled, since the triplet lifetime of **13** is much greater than that of cyclohexadienones which undergo the rearrangement. Radiationless decay directly from the spectroscopic dienone triplet to the ground state is suggested to be of negligible importance, so that inefficiency in the rearrangement results from return to ground state from some intermediate on the pathway to product. In such a situation, dienone triplet lifetimes are determined only by the rate constant k_r for conversion to the next intermediate along the reaction pathway, *i.e.*, $\tau_0 = 1/k_r$. Such an interpretation is consistent with the fact that calculated radiationless decay rate constants for cyclohexadienones, assuming inefficiency is due to direct triplet decay,[7,8,10,20] are orders of magnitude too large to be ascribed to a direct relaxation process.[23,24]

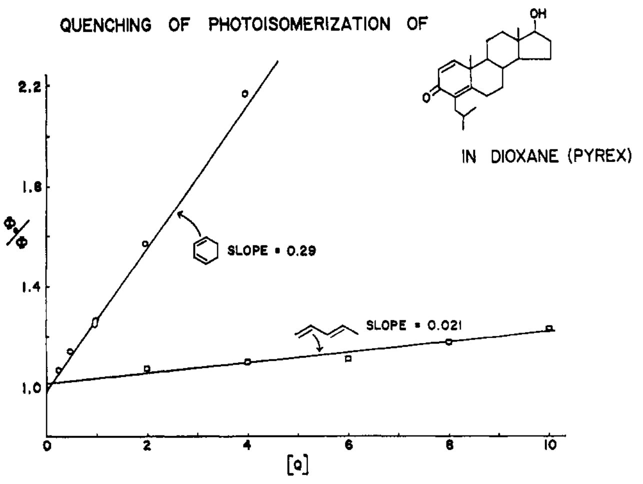
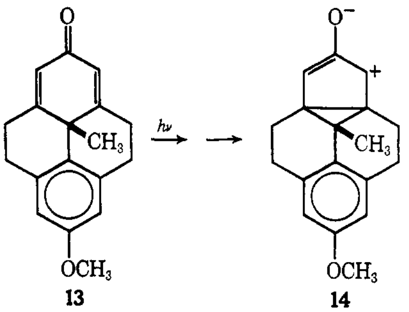


Figure 1. Quenching of the photoisomerization of Δ^1-4-isobutyltestosterone (**3e**) by 1,3-cyclohexadiene and *trans*-piperylene.



13 **14**

However, even k_r values calculated on the basis that $k_r = 1/\alpha\tau_0$ do not show a general trend as the substituent is changed (Table IV). If k_r is determined by the rate constant for bridging, *i.e.*, **10** → **11**, it makes sense that k_r should increase as C-4 goes from secondary to tertiary (*i.e.*, R = H to alkyl), due to stabilization of the intermediate **11** by the alkyl group.

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(19) P. J. Wagner, *J. Amer. Chem. Soc.*, **89**, 5715 (1967); P. J. Wagner and I. Kochevar, *ibid.*, **90**, 2232 (1968).

(20) D. I. Schuster, A. C. Fabian, N. P. Kong, W. C. Barringer, W. V. Curran, and D. H. Sussman, *ibid.*, **90**, 5027 (1968).

(21) J. S. Swenton, E. Saurborn, R. Srinivasan, and F. I. Sonntag, *ibid.*, **90**, 2990 (1968). For a comment on this paper, see ref 8, footnote 48.

(21a) NOTE ADDED IN PROOF. Recent experiments indicate, however, that zwitterions can be trapped by nucleophilic reagents, and lumiketone formation can be prevented. The two processes appear to be kinetically competitive; D. I. Schuster and K. Liu, unpublished results.

(22) H. E. Zimmerman and G. Jones II, *J. Amer. Chem. Soc.*, **91**, 5678 (1969); **92**, 2753 (1970).

(23) P. J. Wagner, *Mol. Photochem.*, **1**, 71 (1969); P. J. Wagner and D. J. Bucheck, *J. Amer. Chem. Soc.*, **91**, 5090 (1969).

(24) D. I. Schuster and W. V. Curran, *J. Org. Chem.*, **35**, 4192 (1970).

For monocyclic dienones, such as the 4,4-diphenyl- and 4-methyl-4-trichloromethyl compounds, the low-temperature phosphorescence is derived from a triplet of energy 67–68 kcal/mol and shows vibronic splitting characteristic of emission from an n,π^* triplet.[7,8] Phosphorescence from ring-fused cyclohexadienones, such as α-santonin, 6-epi-α-santonin,[25a] and several of the compounds used in this study (**3c**, **3d**, and **3e**),[25b] shows in contrast a very broad phosphorescence in 2-methyltetrahydrofuran at 77°K. The origin of the phosphorescence in these compounds is at 400 ± 5 nm (71 kcal/mol), with a maximum at 450 nm for **3c**, **3d**, and **3e**.[25b] The $S_0 \rightarrow T_{n,\pi}$ absorption for **3c**–**3e**, obtained by the phosphorescence excitation technique,[26] barely overlaps the onset of the phosphorescence. A gap between this absorption band and the phosphorescence is noted for 6-epi-α-santonin and α-santonin[25a] at 4.2°K where the spectra are much better resolved, an effect already noted with a series of steroidal cyclohexenones.[27]

The presence of a gap between the $S_0 \rightarrow T_{n,\pi}$ absorption and the phosphorescence indicates the emission is occurring from some other triplet state of lower energy, presumably a $T_{\pi,\pi}$ state, which is confirmed by the phosphorescence lifetime, polarization effects, and heavy atom effects.[25,27] The implication is clear that in compounds **3c**–**3e** as in the other cases,[25,27] the lowest $T_{n,\pi}$ and $T_{\pi,\pi}$ states are quite close in energy.[28] Even if $T_{n,\pi}$ is not the lowest triplet, it may be populated at room temperature, and the photochemistry may originate from this state.[25a,28a] *In any case, it is likely in these systems* that there is substantial mixing between the two lowest triplets, and it may be pointless to attribute the photochemistry to one or the other of the two states.

Since the spectroscopic triplet states of these fused-ring cyclohexadienones are approximately 70 kcal/mol above the ground state, it is difficult to understand the differences in quenching efficiencies observed here and elsewhere[10,20] with dienes whose triplet excitation energies are below 60 kcal/mol. One possible explanation is that relaxation from the spectroscopic triplet **10** is extremely rapid in these cases in solution to produce a triplet whose energy may be around 60 kcal/mol[29] and which may have a geometry approximating that of the 3,5-bonded structure **11** or results from some other geometric distortion.[22] Results of studies in which some model cyclohexadienones were used as sensitizers of olefin isomerization and dimerization[10] are consistent with this postulate.[30]

Experimental Section

Infrared spectra were taken on a Perkin-Elmer Model 337 grating infracord spectrophotometer. Ultraviolet spectra were recorded on a Cary Model 15 spectrophotometer. Nuclear magnetic resonance spectra were taken using a Varian Model A-60 spectrometer using tetramethylsilane as an internal reference. Analytical gas chromatographic analyses were performed on either an F & M Model 810 or 5750 chromatograph, while preparative work was done on an Aerograph Model A-700 chromatograph.

Materials and Solvents. The testosterone (mp 154–155.5°) and Δ^1-testosterone (mp 169.5–172°) were obtained from Steraloids, Inc., and were used without further purification. Reagent grade benzene, ether, ethyl acetate, and dioxane (Baker or Mallinckrodt) were used for chromatography and photolysis studies. The *tert*-butyl alcohol (Baker) and tetrahydrofuran (Fisher) were dried over molecular sieves before use.

Preparation of 4-Isobutyltestosterone. The procedure, based on that of Atwater,[12a] is illustrative of that for the other 4-alkyltestosterones. (For complete details, see ref 4b.) To a boiling solution of 2.4 g (0.062 g-atom) of potassium in 140 ml of *tert*-butyl alcohol was added 12.0 g (0.042 mol) of testosterone dissolved in 200 ml of hot *tert*-butyl alcohol. The solution was heated to reflux, and to it was added a solution of 7.73 g (0.042 mol) of 1-iodo-2-methylpropane in 300 ml of *tert*-butyl alcohol over a 3-hr period under a nitrogen blanket. After heating at reflux for an additional 0.5 hr, the mixture was cooled and acidified with concentrated hydrochloric acid. Water was added and the *tert*-butyl alcohol was removed under reduced pressure. The aqueous layer was extracted four times with 50-ml portions of benzene. The combined extracts were concentrated and put onto a 550-g silica gel column, 59 mm in diameter. The column was eluted with (1) 1500 ml of benzene, (2) 2000 ml of benzene–5% ethyl acetate, (3) 2000 ml of benzene–10% ethyl acetate, and (4) 7500 ml of benzene–10% ethyl acetate. Fraction 4 yielded 5.05 g (35%) of 4-isobutyltestosterone, **7e**. The material was recrystallized from ligroin–ether, mp 125–126°. Spectral data are given in Table I.

Preparation of 4-Alkyltestosterone 17-Tetrahydropyranyl Ether (8).[13] To 90 ml of dry tetrahydrofuran was added 0.01 mol of the 4-alkyltestosterone, 9 ml (0.10 mol) of dihydropyran, and 0.4 ml (0.005 mol) of concentrated hydrochloric acid. After aging overnight, the solution was neutralized with 6 ml of 5% sodium hydroxide solution added with vigorous stirring. The solution was concentrated *in vacuo* and the residue taken up in water and extracted with three 30-ml portions of petroleum ether. The combined extracts were taken to dryness *in vacuo* and the residue chromatographed on a 75-g silica gel column (21 mm diameter). The product was eluted with benzene–5% ether. The oily product, which had no OH band in the ir spectrum, was used without further purification. This same procedure was used for all of the 4-alkyltestosterones.

Preparation of Δ^1-4-Isobutyltestosterone (3e). This procedure is illustrative of that used for preparations of the other 4-alkyldehydrotestosterones, **3**. To 120 ml of benzene was added 4.28 g (0.01 mol) of the tetrahydropyranyl ether **8e**, 4.10 g (0.018 mol) of 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ), and 3.0 ml of glacial acetic acid. The resulting solution was heated at reflux under nitrogen for 30–40 hr. The solution was cooled, filtered, and taken to dryness *in vacuo*. The residue was chromatographed on a column (21 mm diameter) of 75 g of Merck alumina, eluting with (1) 100 ml of benzene, (2) 200 ml of 20% ether–benzene, (3) 200 ml of 50% ether–benzene, (4) 900 ml of ether, and (5) 300 ml of 20% ethyl acetate–ether. The product **3e** was isolated from fraction 5. Recrystallization from ligroin–acetone gave 1.14 g (32%) of **3e**, mp 179–180°. Spectral data are given in Table II.

Anal. Calcd for $C_{23}H_{34}O_2$: C, 80.6; H, 10.0. Found: C, 80.6; H, 10.2.

Photolysis of Dehydrotestosterones 3. Isolation of Lumiketones 4. A solution of 150 mg of the Δ^1-testosterone **3** in 9 ml of dioxane was photolyzed for 5–13 hr at 2537 Å using a Hanau 6/20 low-pressure lamp, until the conversion of starting material was about 75% by glpc analysis. The solution was taken to dryness *in vacuo* and the residue was chromatographed on a column (12 mm diameter) of 15 g of Merck alumina, eluted with varying proportions of ether–benzene. In the case of **4e**, the product was eluted with 30% ether–benzene in 67% yield, and gave only one peak in the

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[25] (a) G. Marsh, D. R. Kearns, and M. Fisch, *J. Amer. Chem. Soc.*, **92**, 2252 (1970). (b) We are grateful to Dr. Kearns and Dr. Marsh for low-temperature absorption and emission measurements on several of the cyclohexadienones **3** used in this study, as part of their general investigation of such systems. Details of this work will be published in due course.

[26] D. R. Kearns and W. A. Case, *J. Amer. Chem. Soc.*, **88**, 5087 (1966); A. Marchetti and D. R. Kearns, *ibid.*, **89**, 768 (1967); R. F. Borkman and D. R. Kearns, *Chem. Commun.*, 446 (1966).

[27] D. R. Kearns, G. Marsh, and K. Schaffner, *J. Chem. Phys.*, **49**, 3316 (1968); G. Marsh, D. R. Kearns, and K. Schaffner, *Helv. Chim. Acta*, **51**, 1890 (1968).

[28] It is likely that the overlap of the $S_0 \rightarrow T_{n,\pi}$ absorption and the emission in compounds **3** would not be observed at higher resolution at 4.2°K: D. R. Kearns, private communication.

[28a] NOTE ADDED IN PROOF. For a related example of reaction *via* equilibrium concentrations of upper n,π^* triplets, see P. J. Wagner, A. E. Kemppainen, and H. N. Schott, *J. Amer. Chem Soc.*, **92**, 5280 (1970).

[29] A suggestion to this effect has been made by P. J. Wagner and G. S. Hammond, *Advan. Photochem.*, **5**, 21 (1968), especially p 113 ff.

[30] The diffuseness in the low-temperature emission spectra can also be attributed to differences in geometry of the emitting triplet and the ground state.[25a]

vapor chromatogram. Spectral data for the lumiketones are given in Table III. The mass spectrum for **4e** (mol wt 342) had major peaks at m/e 342, 327, 299, 135, 121, 107, 105, 91, 79, 57, 55, 43, and 41 (base peak).

Quantum yields were measured as described previously[8] at 254 ± 10 nm using a Bausch and Lomb Model 33-86-25 high-intensity grating monochromator with a 200-W super-pressure mercury source. The quantitative analysis for the lumiketones was carried out by glpc on an SE-30 column (see below). Measurements were normally made in reagent grade dioxane as solvent. The effect of of possible impurities in the solvent was determined by studying the per cent conversion of **3a** → **4a** with and without added quencher in duplicate solutions in reagent dioxane and dioxane purified by the method of Wiberg.[31] In all cases, yields of **4a** were 10–12% higher in the purified compared with the unpurified dioxane. Accordingly, quantum yield data obtained in unpurified dioxane have been increased by 11% and the corrected data are given in Table IV. Such corrections are not necessary in the quenching experiments (below) where relative product yields with and without added quencher were determined. Data in Table IV are averages of duplicate determinations.

Quenching Studies. All quenching studies were run on a precision "merry-go-round" apparatus immersed in a water bath at 34 ± 1°. A 450-W high-pressure mercury lamp was used as the light source, and Pyrex filters were used to cut out light below 3000 Å. Solutions containing equal amounts of steroid and graduated amounts of quencher were adjusted to 4 ml by the addition of dioxane. The solutions were placed in the merry-go-round and photolyzed for 10–15 min. Tetracosane, as an internal standard, was then added, and the solutions were analyzed for lumiketone by glpc on a 4 ft 10% SE-30 on Chromosorb W, DMCS-A/W column. The 1,3-cyclohexadiene and *trans*-piperylene used as quenchers were obtained from Chemical Samples Co. and distilled before use.

Peaks near the solvent peak on the vapor chromatogram typical of 1,3-cyclohexadiene and *trans*-piperylene dimers were observed in all the runs, and increased in relative size as the extent of quenching increased.

Gas Chromatographic Analysis. The amount of lumiketone was measured by glpc using a 1/8 in. × 4 ft 10% SE-30 on Chromosorb W, DMCS-A/W column. The oven temperature was generally 250–255°, although in certain cases, temperatures from 225 to 260° were used. Measured amounts of tetracosane were added to the lumiketone solutions before analysis.

To determine the gas chromatography response factors, standard solutions of tetracosane and the pure lumiketones were prepared. These factors were redetermined every time an analysis for lumiketone was run, and the standard solution was injected frequently during a run. The retention times for the dienones and lumiketones are listed in Table V along with those of the tetracosane standard.

Table V

Dienone	Oven temp, °C	Retention times,[a] min		
		Tetracosane	Lumiketone	Dienone
3a	250	2.6	3.6	6.0
3b	225	6.3	7.7	14.7
	240	3.3	4.4	8.0
	255	2.3	3.2	5.6
3c	255	2.3	3.5	6.2
3d	255	2.3	5.1	9.6
3e	255	2.3	4.7	8.2
3f	255	2.3	5.7	11.2

[a] On a 1/8 in. × 4 ft 10% SE-30 on Chromosorb W, DMCS-A/W column. Injection port, 270°.

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[31] K. B. Wiberg, "Laboratory Techniques in Organic Chemistry," McGraw-Hill, New York, N. Y., 1960, p 245 ff.

Perturbed [12]Annulenes. The Synthesis of Pyracylenes

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Abstract: Utilizing PMO theory, pyracylene is described as a [12]annulene with an internal vinyl cross-link. As such, it should be an unusually good model for a planar [12]annulene. To examine such a hypothesis, the synthesis of pyracylene, 1,2-dibromopyracylene, and 1,2-diphenylpyracylene was achieved. The key step involved a polybenzylic bromination. After introduction of the first bromine, subsequent hydrogen atom removal involved predominantly, if not exclusively, the β-hydrogen trans to that bromine. Iodide-promoted elimination of the thus formed dibromide introduced the crucial bridging double bonds. Polarographic reduction suggested the presence of an empty approximately nonbonding molecular orbital in agreement with the above model. Dramatic support arose from their nmr spectra which show the protons shifted to exceptionally high fields. These abnormal shifts are interpreted in terms of a paramagnetic ring current—in excellent accord with the proposed peripheral electronic model.

Introduction and Theory

A fundamental question in organic chemistry relates to the net energy change associated with electron delocalization. Inherent in the concepts of resonance theory lies the proposition that electron delocalization increases the stability of the system. Molecular orbital theory refutes that hypothesis and suggests that associated with electron delocalization may be net energy stabilization, no net energy change, or energy destabilization. In the first category fall the well-known $4n + 2$ monocyclic and many related systems; however, experimental verification of the remaining categories remains to be established. Barrelene and [4.4.2]propellapentaene may be representative of molecules in which

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