

## Nucleophilic Attacks on LL (Low LUMO) Substrates. Part 3.<sup>1</sup> Molecular Stacking of 9-Methylenefluorene Derivatives as a Source of Zero-order Reactions

Shmaryahu Hoz,\* Zeev Gross, and Dov Speizman  
Department of Chemistry, Bar-Ilan University, Ramat-Gan 52100, Israel

The reactions of the three activated dibenzfulvene derivatives 9-dicyanomethylene-, 9-dinitromethylene-, and 9-nitromethylene-fluorene (FDCN, FDN, and FN respectively) with NaOH in water containing 1% dioxane were followed at 25 °C. The reactions were found to be zero-order in the substrate and zero-order within a run in the hydroxide. Overall, the reaction was first-order in the hydroxide. Under these conditions zero-order kinetics are also obtained for the reaction of CN<sup>-</sup> with FDCN. 'Normal' first-order kinetics were obtained under these conditions for the reaction of OH<sup>-</sup> with 1,1-diphenyl-2,2-dinitroethylene as well as for FDN when the dioxane concentration was increased to 25% (v/v). It is suggested that owing to their planar structure these substrates undergo efficient stacking in the solution with only a small fraction left as a free reactive monomer at the saturation concentration. A relatively rapid equilibrium between the monomer and the aggregate maintains a constant monomer concentration in the solution. A Tyndall effect of the aggregated particles could not be observed with the naked eye. The particles also pass through a Whatman No. 1 filter paper. However, other observations such as solvent and temperature effects on the absorbance in the u.v. range strongly support the suggested explanation.

Zero-order reactions are rarely encountered and usually attributed to 'chemical' or 'physical' origins. An example of the former is the rate-limiting formation of a nitronium ion in the nitration of aromatic nuclei.<sup>2</sup> On the other hand, saturation of active catalytic sites or rate dependence on light intensity in a photochemical reaction can be considered as a 'physical' origin of zero-order kinetics.<sup>3</sup> To the best of our knowledge, nucleophilic attacks on activated olefins have not been found to obey zero-order kinetics. Our previous studies<sup>1</sup> have demonstrated that nucleophilicity towards olefins of the general structure (1) correlates well with the Ritchie  $N_+$  nucleophilicity scale.<sup>4</sup> However, this study was limited primarily to organic or aqueous-organic solutions since only in these solvents can a normal second-order rate constant be observed.

This paper reports a study of these reactions in water where zero-order kinetics are observed. It is believed to have a 'physical' origin, namely, aggregation of the substrates.

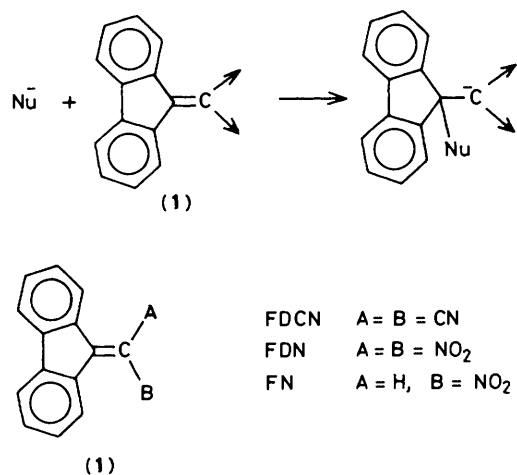
### Results

The three substrates employed in this study were dibenzfulvenes of structure (1).

The majority of the work was performed on 9-(dicyanomethylene)fluorene (FDCN) which unlike 9-(dinitromethylene)fluorene (FDN) is stable when solubilized in aqueous media. Limited measurements were also made with the third substrate, 9-(nitromethylene)fluorene (FN).

The kinetics of the reactions of these three substrates with NaOH and in some cases with NaCN were followed spectroscopically at 25 °C. The products of the hydrolysis reactions were fluorenone and the respective substituted methanes (malononitrile, dinitromethane, and nitromethane) or their conjugated bases.

**FDCN.**—The kinetics of the reactions of FDCN with NaOH (25 °C; concentration ranges were 10<sup>-5</sup>–10<sup>-6</sup> and 0.05–0.001M, respectively) in 1% aqueous dioxane were followed at 350 (λ<sub>max</sub> of FDCN) and 258 nm (λ<sub>max</sub> of fluorenone) simultaneously. The disappearance of FDCN showed pseudo-zero-order kinetics (up to at least 90% reaction), namely, zero-order in the substrate and zero-order in the hydroxide within a run. Overall, the reaction rates (O.D./min) correlate linearly with the hydroxide



concentration. For [OH<sup>-</sup>] > 0.01M, the increased absorption at 258 nm was also zero-order, matching in rate the decrease at 350 nm. However, at low hydroxide concentration (0.0025M) a zero-order decrease in the absorption at 258 nm was first observed (FDCN has significant absorption at this wavelength) followed by a very slow increase indicating a slow formation of fluorenone.

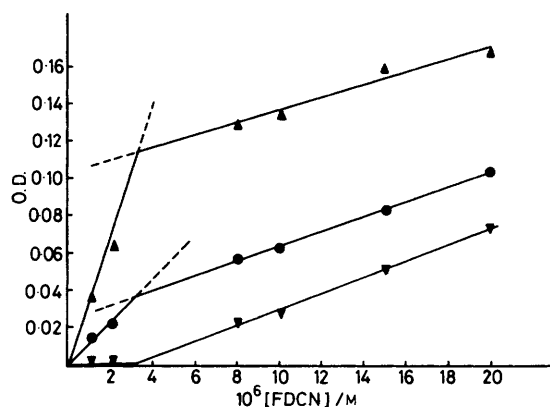
While the disappearance of FDCN was completed in ca. 15 min, fluorenone was formed over several hours. The reaction with NaCN (0.023M) also gave zero-order disappearance of FDCN. The products of this reaction were the respective cyano adduct<sup>1</sup> and the hydrolysis products. On the other hand, the diphenyl analogue of FDCN (1,1-diphenyl-2,2-dicyanoethylene, DPDCN) reacts with hydroxide under these conditions with clear pseudo-first-order kinetics.

Limited spectroscopic studies on FDCN were also performed. Linear Beer-Lambert correlations were found at 269, 350, and 385 nm in 1% and 40% dioxane solutions. The results are given in the Table. When performed in 20% dioxane solutions, a non-linear correlation was obtained (Figure 1). In general, the percentage of the organic component in the water strongly affects both the shape and the extinction coefficients of

**Table.** Logarithms of the extinction coefficients of FDCN as a function of wavelength at 25 °C in aqueous dioxane solutions

$\lambda/\text{nm}$	% Dioxane in H <sub>2</sub> O			
	1%	40%	20% <sup>a</sup>	20% <sup>b</sup>
269	4.172	4.619	4.53	3.538
350	3.059	4.295	4.051	3.594
385	3.927	c	c	3.64

<sup>a</sup> Low-concentration region. <sup>b</sup> High-concentration region. <sup>c</sup> The solutions do not absorb at this wavelength.

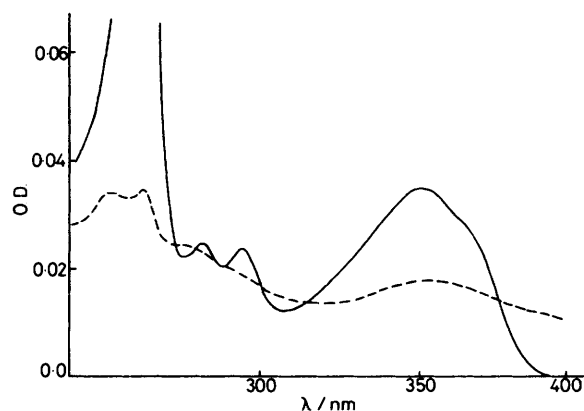


**Figure 1.** A Beer-Lambert correlation for FDCN in a 20% dioxane-water (v/v) solution.  $\blacktriangle$ , 269;  $\bullet$ , 355;  $\blacktriangledown$  385 nm

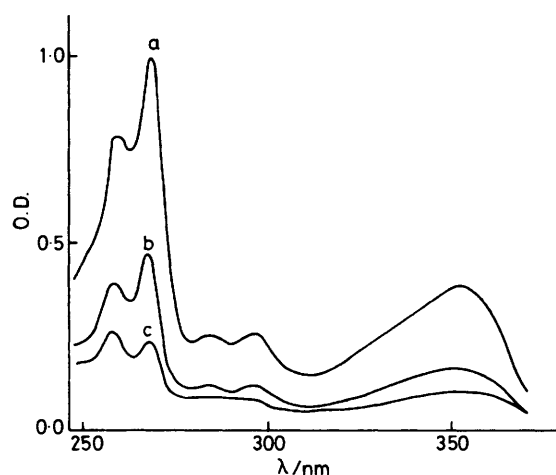
FDCN (Figure 2). Moreover, when additional dioxane (up to 25%, v/v) was added to a solution of FDCN containing 1% dioxane, the FDCN absorption at 350 nm increased by 44% instead of decreasing by the 25% expected on the basis of the dilution ratio. With DPDCN the same experiment showed, as expected, a decrease in the absorbance. The temperature effect on the absorbance was measured in 20% dioxane solution. As can be seen (Figure 3) the absorption increases with increasing temperature. This effect was not observed in 1% and 40% dioxane solutions.

**FDN.**—The kinetics of the reaction of FDN with NaOH (25 °C; concentration ranges were  $10^{-4}$ – $10^{-6}$  and 0.02–0.001M, respectively) in 1% dioxane solutions was followed at 420 and 258 nm. Again, the reactions were pseudo-zero-order but, unlike the case of FDCN, there was no phase lag between the disappearance of the substrate and the formation of fluorenone over the whole range of the  $\text{OH}^-$  concentration employed. In 25% dioxane solutions (ca. 25 °C), the reactions were very fast (a stopped-flow apparatus was used) exhibiting clear first-order kinetics in the substrate ( $k$  ca.  $30 \text{ l mol}^{-1} \text{ s}^{-1}$ ). In 1% dioxane solutions a remarkable linear Beer-Lambert correlation was obtained over a concentration range of  $3 \times 10^{-6}$ – $37 \times 10^{-6} \text{ M}$  ( $r$  0.9966). With this as well as with the other two substrates no Tyndall effect<sup>5</sup> could be observed with the naked eye and filtration through a Whatman No. 1 filter paper did not reduce the solutions' optical density. Another experiment used to search for large particles in the solution involved ultracentrifuge sedimentation. Monitoring at  $\lambda$  250 nm, a 1% aqueous dioxane solution of FDN (ca.  $10^{-5} \text{ M}$ ) showed a band at 200 000 g, indicating the presence of heavy particles in the solution.

**FN.**—Under the conditions detailed above for the 1% dioxane solutions (with the exception that NaOH concentr-



**Figure 2.** Solvent effect on the u.v. spectrum of FDCN. Dashed line, 1% dioxane; full line, 40% dioxane in water (v/v)

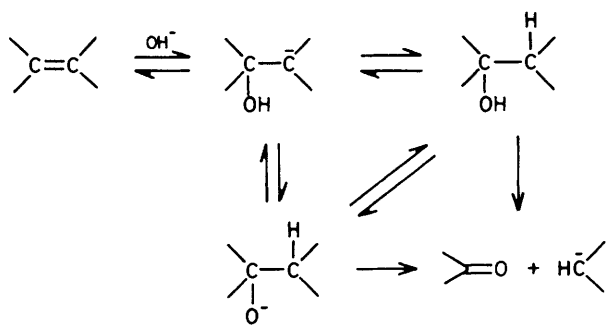


**Figure 3.** Temperature effect on the u.v. spectrum of FDCN in 20% dioxane-water solution (v/v): (a) 55; (b) 30; and (c) 10 °C

ations were larger: 0.012–0.5M) the same pseudo-zero-order kinetics was observed at 359 nm (disappearance of FN). The formation of fluorenone (258 nm) lagged significantly behind the first process and is not a zero-order reaction.

## Discussion

Nucleophilic attacks on electrophilic olefins have been thoroughly studied by many groups.<sup>6</sup> A very detailed mechanistic analysis of these reactions has recently been reported by Bernasconi *et al.*<sup>7</sup> The mechanism of the hydrolysis of analogous diarylethylenes by  $\text{OH}^-$  involves a large number of elementary steps (Scheme). The identity of the rate-determining step is governed by the characteristic features of the system such as substituents, pH, catalysts, *etc.* None of the above studies (mentioned in refs. 6 and 7) exhibits zero-order kinetics nor could such a case be invoked on the basis of any reasonable combination of the elementary steps of the Scheme. Therefore, the working hypothesis adopted in this paper is that the origin of the observed zero-order reaction is of a 'physical' rather than a 'chemical' nature. Supporting this are the following observations. The reaction with  $\text{CN}^-$  whose mechanism is much simpler than that with  $\text{OH}^-$  and which involves only one step (its reaction with FDCN is reversible with the reaction in the reverse direction being very slow compared with the forward one) also displays zero-order



Scheme.

kinetics. It is also somewhat unlikely that a mechanistic peculiarity which could lead to the observed phenomenon will be shared by substrates with different activating groups such as nitro and cyano covering a reactivity range of over four orders of magnitude. Improving the solubilities of the substrates by adding an organic component to the water effects a change from zero- to first-order kinetics in the substrates, thereby also suggesting a 'physical' rather than 'chemical' origin of the effect.

An explanation which is consistent with the observed results is that, in water, the substrates employed exist partly as aggregates and partly as free monomers. In the presence of aggregates, in an equilibrated system, the monomer concentration is that of a saturated solution. This concentration remains constant and does not increase when the total concentration of the substrate introduced is increased. In order to explain the zero-order dependence in the substrate, two additional assumptions must be made. First, the reactivity of the free monomer is much larger than that of a substrate molecule embedded in the aggregate. Second, the rate at which the solution is depleted of the free monomer by means of the chemical reaction is much slower than the rate at which the aggregates dissolve to give free monomer. Fulfilment of these conditions will result in an observed zero-order reaction in the substrate since the reactive concentration of the substrate (monomer saturation concentration) remains constant throughout the reaction. Towards the end, however, one of the conditions (probably the second) will break and the order of the reaction in the remaining substrate will gradually shift from zero to one. This seems to be the case for all three substrates, thus explaining the observed zero-order reaction. Addition of dioxane increases the solubility of the substrate. A homogeneous solution is obtained and, as was indeed observed, a normal first-order reaction in the substrate was observed.

The following observations strongly support the monomer-aggregate assumption. The first is the ultracentrifuge experiment which shows unequivocally the presence of sizeable particles in the solution. The second is the effect of added dioxane on the O.D. of the solution. For a molecule with a sufficiently high extinction coefficient, the specific absorption (O.D. per mole) is expected to be larger in the free monomer than when embedded in a sizeable aggregate. In the latter, only the frontal layers (with respect to the beam of light) will take part in the photon-absorption process whereas all the rest of the molecules remain in the 'shadow' and therefore do not contribute to the light absorption (this is somewhat compensated by the Rayleigh scattering effect), thus reducing the average specific absorption. As was mentioned in the Results section, addition of dioxane to form a 25% dioxane-water solution caused, contrary to the expected dilution effect, an actual increase of 44% in the absorbance of an FDCN solution in water. This is in contrast to the decrease in the absorbance (proportional to the dilution factor) observed for the analogous

compound DPDCN. The third observation which supports the assumption of aggregation in the aqueous solution is the absorbance-concentration dependence for FDCN in 20% dioxane-water solution. This concentration of dioxane was chosen since, as indicated by the kinetic order, the substrate (FDCN) in 1% dioxane solution exists mainly as an aggregate whereas in 40% dioxane it is practically completely converted into the free monomeric state. It was therefore expected that at an intermediate dioxane concentration, the two types of species will play a comparable role. This is indeed observed in Figure 1, which shows a Beer-Lambert plot for FDCN in 20% dioxane solution at three wavelengths. In each plot two zones can easily be detected. Up to a concentration of *ca.*  $4 \times 10^{-6}$  M, the slopes of the plots for  $\lambda$  269 and 355 nm are steep and show extinction coefficients easily attributable to the monomer. This concentration is apparently the 'critical aggregation concentration' beyond which the substrate starts to aggregate. A further increase in the concentration is accompanied by a much smaller increase in the absorbance and, as was shown before, the aggregates absorb light to a lesser extent compared with the monomers on a molecular basis. At  $\lambda$  385 nm, the monomer practically does not absorb light. The initial portion of the plot is therefore flat with O.D. = 0 and only when aggregation commences does the O.D. increase. Finally, the fourth observation is the temperature-dependent absorption. Normally, increasing the temperature results in increased solubility of most of the known chemical compounds. An aggregate, if it exists, is likely to respond to increased temperature by releasing more monomer into the solution which is expected to result in a change in the O.D. of the solution. In a 1% dioxane solution this has not been observed probably due to the very low solubility of the monomer in this medium, even at elevated temperatures. However, in 20% dioxane solution the temperature has an immense effect as can be seen in Figure 2, thus supporting further the suggested explanation.

There are three additional observations that need some clarification since at first glance they seem to be inconsistent with the suggested aggregation model. These are (a) the absence of a decrease in the O.D. of the solution after filtration with Whatman No. 1 filter paper, (b) the inability to observe a Tyndall effect<sup>5</sup> with the naked eye, and (c) the observed linear Beer-Lambert plots in 1% dioxane solutions for FDN and FDCN. The first two can easily be accounted for by the high dilution of the solutions and the small size of the particles. The third one is somewhat surprising since elementary textbooks always associate aggregation with deviations from Beer-Lambert plots.<sup>8</sup> It should be noted, however, that in order for such a deviation to be observed at least two conditions must be fulfilled. A phase change must take place within the range of the concentrations measured and the molar extinction coefficient of the material in the two phases (*i.e.* monomer and aggregate in this case) should be different. In the present cases, however, at 1% dioxane solutions the absorbance is due essentially to the aggregate alone and therefore the Beer-Lambert law should be obeyed.<sup>9</sup> (This assumes that the average optical properties of the aggregates are not affected by their total concentration.) One can therefore conclude that the observed phenomena are consistent with the suggested monomer-aggregate system.

Aggregation or micelle formation in aqueous solutions is usually observed when the substrates contain long hydrophobic alkyl chains.<sup>10</sup> The ratio between the sizes of the hydrophobic and hydrophilic parts of the substrates employed in this study seems intuitively not to support such an enhanced aggregation, especially when compared with the analogous diphenyl derivatives. We believe that the planar structure of the fluorenylidene substrates enhances their stacking ability thereby leading to the observed behaviour. The large energy gain obtained by the stacking of these molecules is reflected in

their relatively high m.p.s (238, 189, 134, 136, 146—147, and 87 °C for FDCN, FDN, FN and the diphenyl analogues respectively).<sup>11</sup>

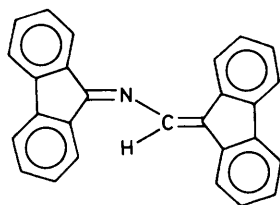
Finally the phase lag between the destruction of the double bond ( $\lambda > 300$  nm) and the formation of fluorenone ( $\lambda$  258 nm) will be addressed. It probably stems from accumulation of the hydroxy-adduct in the reaction which decomposes relatively slowly to the fluorenone product. Apparently its rate of decomposition is affected by the nature of the activating group and the hydroxide concentration.

**Conclusions.**—When each of the three substrates FDCN, FDN, and FN is introduced into an aqueous solution containing 1% dioxane, the compounds tend to aggregate. The minute amounts of monomer present in the solution at its saturation concentration are practically the only reactive species. The reactions are zero-order in the substrates since, apparently, the rates at which the aggregates dissolve in the medium are faster than the rates at which the monomers are consumed, thus maintaining a constant monomer concentration in the solution.

### Experimental

**Instrumentation.**—Electronic spectra were taken with Perkin-Elmer 402 and Gilford 2400 spectrophotometers. The kinetics of the reactions were followed with the Gilford and a Durrum D-110 stopped-flow spectrophotometer, both attached to a PDP11/40 minicomputer for data handling. The ultracentrifuge used was a Beckman model E analytical ultracentrifuge. Attempts to observe the Tyndall effect were performed with a regular 'sunlight' lamp and a fluorescent cell.

**Substrates and Solvents.**—All substrates are known compounds and were prepared according to literature procedures: 9-(dicyanomethylene)fluorene (FDCN),<sup>11a</sup> 1,1-diphenyl-2,2-dicyanoethylene (DPDCN),<sup>11d</sup> 9-(dinitromethylene)fluorene (FDN),<sup>11b</sup> 9-(nitromethylene)fluorene (FN).<sup>11c</sup> In employing the procedure of ref. 11c for the preparation of FN it was found that the FN was contaminated by large quantities of a compound tentatively assigned structure (2), fluoren-9-



(2)

ylidene(fluoren-9-ylidenemethyl)amine. FN was isolated by column chromatography on silica with either  $\text{CHCl}_3$  or  $\text{CCl}_4$ . The desired product FN is eluted after contaminant (2). Water was doubly distilled and the dioxane was purified according to a published procedure.<sup>12</sup>

**Kinetic Measurements.**—The kinetics of the reactions of the three substrates were determined by using the Gilford 2400 spectrophotometer which was equipped with a circulating bath. The temperature within the cell compartment was  $25 \pm 0.1$  °C. The cells containing the aqueous dioxane NaOH solutions were preincubated in the cell compartment for ca. 15 min. The reaction was initiated by injecting 10  $\mu\text{l}$  of the substrate in dioxane into the cells. [In calculating the concentration of the dioxane (v/v) the volume of the added substrate-dioxane solution was also taken into account.] The fast reactions, namely those of FDN with  $\text{OH}^-$  in 25% dioxane, were measured on a stopped-flow apparatus at ambient temperature ( $25 \pm 2$  °C).

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