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Chemical Reactions in Liquid Crystalline Solvents: Anti-Arrhenius Behavior as a Consequence of Nematic-Smectic A-Reentrant Nematic Phase Transitions

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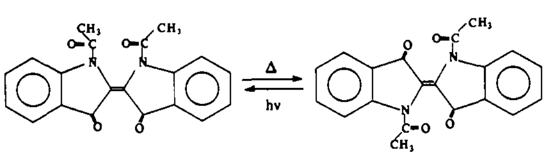
Ever since the early days of liquid crystal research, there has been an interest in the modulation of chemical reactivity by the anisotropic and orientational behavior of the various phases.[1] In cholesteric media, the emphasis in recent years has been placed on the possibility of asymmetric induction.[2-7] A review of reactions in thermotropic phases has recently appeared.[8] Nematic lyotropic liquid crystals have been shown to be useful media for chemical reactions, showing marked discontinuities in reaction rates through the phase transitions from rod-like to disk-like to sphere-like phases.[9]

It occurred to us that the phenomenon of reentrance[10] affords a phase sequence with decreasing temperature in which one proceeds from less ordered to ordered and then *to less ordered again*. Our expectation was that a reaction run in such a medium might show a decrease in rate as the smectic phase is entered, but would increase in rate as the nematic phase is reentered. Such anti-Arrhenius behavior would be extremely interesting to find and is very rare in chemical systems.[11-13]

In this work, the effect of the nematic-smectic A-reentrant nematic phase transitions on the kinetics of the thermal isomerization of *cis*-*N*,*N*′-diacetylindigo (*cis*-DAI) is studied. (See eq 1.) A liquid crystal mixture of 4-*n*-heptyl-4′-cyanobiphenyl (7CB), 4-(*n*-octyloxy)-4′-cyanobiphenyl (8OCB), and 4-*n*-pentyl-4′-cyanoterphenyl (5CT) in the ratio 73:18:9 by weight shows a nematic phase between 65.6 and 26.9 °C, a smectic A phase between 26.1 and 10.1 °C, and a reentrant nematic phase below 10.1 °C. This particular liquid crystal mixture has the advantages that the reentrant nematic phase is stable, does not supercool, and shows reversible enantiotropic transitions.[14]



(1)

cis trans

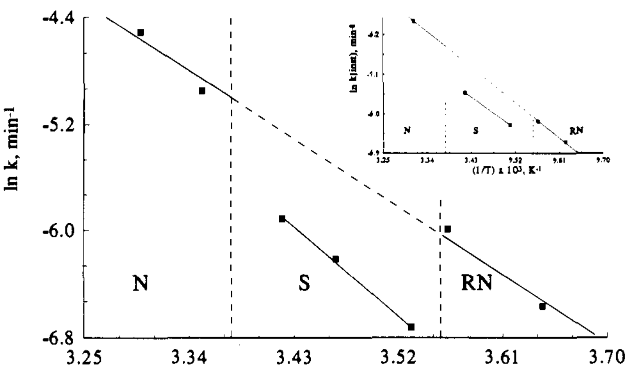


Figure 1. Arrhenius plot of the isomerization of *cis-N,N′*-diacetylindigo in 7CB/8OCB/5CT, 73:18:9 wt %. Inset, Arrhenius plot of the instantaneous rate constants. The dashed lines indicate the phase transitions; N, nematic; S, smectic; and RN, reentrant nematic.

A solution of the trans isomer of DAI[15-17] in the liquid crystal mixture (ca. 10^{-3} M) was placed between two quartz plates separated by a 0.17-mm polyester spacer. The addition of the solute causes a depression of the phase transition temperature of the solvent of approximately 1 °C. The cis form was obtained in situ by irradiation with a 150-W halogen-tungsten lamp reflected on a cold mirror provided with a filter that passes wavelengths greater than 500 nm.

Periodically the sample were observed under a polarizing microscope to assure that precipitation of product or product-reactant mixture did not occur. No problems were encountered upon successive irradiations (ca. 10 times) or keeping the sample in the dark for several days. The kinetics of the thermal isomerization were followed by monitoring the absorption at 565 nm (where the trans isomer has a maximum) for 3-7 half-lives of the cis isomer.

Figure 1 is an Arrhenius plot vs $1/T$ of the mean values of at least three measurements of the rate constant obtained from the slope of a first-order plot of ln ($OD_\infty - OD_t$) versus time. Due to the slow rate of isomerization, values for OD_∞ were obtained either by heating the sample to the isotropic phase (70 °C) until equilibrium occurs, followed by measurement at the original temperature, or by simply waiting for stabilization for many hours at the operational temperature. The rate constants and the OD_∞ values obtained in this way were within 10% of values obtained for the same parameters by the method of Swinbourne.[18]

The rate constants in the reentrant nematic and smectic phases showed the expected first-order plot. A typical plot consists of 60-100 data points and shows a correlation coefficient of $r > 0.99$. However, in the nematic phase, deviations from first-order behavior were observed, with the extent of departure increasing with successive determinations on the same sample. It is well-known that *cis*-DAI has a tendency to crystallize from a trans isomer solution upon irradiation,[19] and this factor may be responsible for the deviation from first-order behavior.

The Arrhenius plot (Figure 1) of the rate constants shows the anticipated discontinuities at the phase transitions. The rate constants for the nematic and reentrant nematic phases fit a straight line. However, entrance and departure from the smectic phase show an abrupt decrease and increase in the rate, respectively.

Further evidence for this behavior was found by determining the instantaneous rate constants of a single sample at different temperatures. After determining the changes in the OD during 0.1-0.3 half-life, the solution was rapidly heated (or cooled) with a circulating bath prestabilized to the desired temperature. From the slope of a plot of the changes in OD with time, two sets of

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[11] We are aware of two other cases of anti-Arrhenius behavior. The first is associated with reactions in frozen solutions,[12] and the second in electron-transfer reactions.[13]
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[15] The *trans-N,N′*-diacetylindigo was synthesized and purified as described in refs 16 and 17. The final material has mp 254-256 °C (lit. mp 256-257 °C;[19] 268-269 °C;[16] 263-264 °C[17]). IR (KBr): 1700, 1685, 1600 cm^{-1} (lit.[19] 1690, 1680, 1595 cm^{-1}).
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rate constants (k(inst)) were determined for heating and cooling. The Arrhenius plot of these rate constants is also shown in Figure 1.

Activation enthalpies determined in the nematic phases and in the smectic phase are the same ($\approx$15 kcal mol^{-1}) within experimental error and also are similar to that obtained in benzene.[16,19] However, because of the small temperature range, these values are inherently inaccurate. The rate constants in the liquid crystalline phases are approximately 10 times as high as those in benzene, a solvent with a considerably lower viscosity. Ganapathy et al.[15] have found that, in a cholesteric mixture, DAI has an activation parameter similar to that in benzene and the isomerization reaction is not affected by the viscosity of the solvent. The mixed cyano-substituted oligophenyl would be expected to have a much greater dielectric constant than benzene, and this factor might be responsible for the higher reactivity observed. As for the difference in reactivity between the smectic and nematic phases, the smectic phase is clearly a more ordered microenvironment, adopting a layer-like structure as a consequence of the strong dipole–dipole interactions among cyano groups.[10] Formation of the transition state for the isomerization may be less favorable in this rigid microenvironment than in the corresponding nematic phases.

Work is continuing in an attempt to explore the generality of anti-Arrhenius behavior associated with reentrance.

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Chemically Induced Modification of Cofactor Specificity of Glucose-6-phosphate Dehydrogenase[†]

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Changing recognition of enzymes and other molecules in a desired manner has been accomplished using enzyme modifications,[1a–c] temperatures,[1d–f] solvent,[1g] substrate modifications,[1h,i] and chemically designed materials.[1j–m] In this paper we describe a general chemical approach to modifying cofactor specificity of NADP dependent enzymes. A vanadate ester derivative of NAD has the potential of being a structural and functional analog of 2′-NADP. Vanadate ($H_2VO_4^-$ or HVO_4^{2-}) is a good analog for phosphate ($H_2PO_4^-$ or HPO_4^{2-}), suggesting that organic vanadates will be good analogs of organic phosphates.[2,3] In aqueous solutions, vanadate will react on a millisecond time scale with hydroxyl groups in organic ligands and spontaneously form organic vanadate esters (eqs 1 and 2 in Figure 1), which are analogous to organic phosphates.[2,3] Primary, secondary, and tertiary alcohols will all react with vanadate to form vanadate esters, and the formation constant ranges from 0.1 to 10.[3] When organic vanadate esters form as in a solution of glycerol and vanadate, enzymes such as glycerol-3-phosphate dehydrogenase[4,5] are able to recognize and

Reaction: NAD and Vanadate

$$ROH + H_2VO_4^- \rightleftharpoons ROVO_3H^- + H_2O \qquad (1)$$

$$ROH + ROVO_3H^- \rightleftharpoons (RO)_2VO_2^- + H_2O \qquad (2)$$

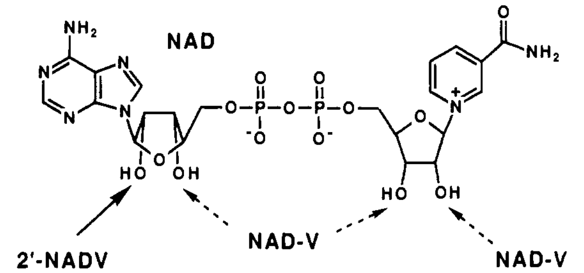

Figure 1. The vanadylation sites of NAD as well as the general reactions to form vanadate esters (eq 1) and vanadate diesters (eq 2).

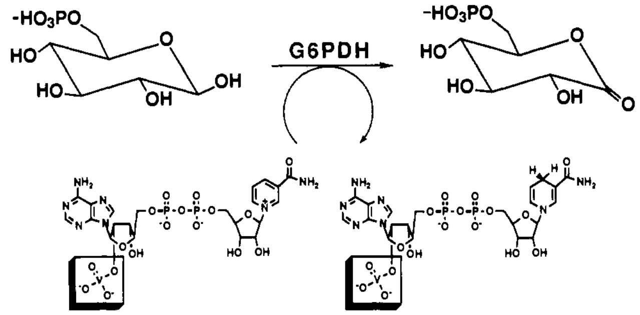

Figure 2. The reaction of glucose 6-phosphate with NADV catalyzed by glucose-6-phosphate dehydrogenase to form 6-phosphogluconate and NADVH.

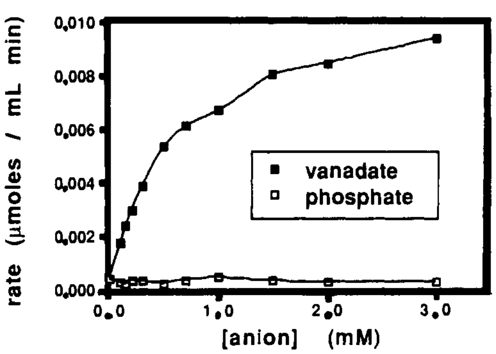

Figure 3. Rates of G6PDH reaction by addition of vanadate and phosphate to assay solutions containing NAD. Assay solutions contained 50 mM TAPS, 80 mM KCl, 2.0 mM NAD, 5.0 mM G6P, approximately 5.5 mg/mL G6PDH, and from 0.0 to 3.0 mM vanadate or from 0.0 to 3.0 mM phosphate at pH 9.0.

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