of **6c**, **5a** had formed a small amount of **6a**, the integral for the *o*-methyl of **5d** was somewhat smaller, and no change for **5e**; after 29 h of irradiation, **5a** had formed 10% of **6a** with no decrease in the integral for the *o*-methyl group of **5a**, the integral for the *o*-methyl group of **5d** had decreased to 67% of the value of the integral of the methyl of the ethyl group, and no change for **5e**.

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Registry No. **5a**, 56290-54-1; **5b**, 7402-38-2; **5c**, 116971-61-0; **5d**, 51725-82-7; **5e**, 61001-54-5; **6a**, 116971-62-1; **6b**, 116971-63-2; **6b′**, 116971-64-3; **6c**, 116971-65-4; **7a**, 13615-40-2; **7b**, 50703-94-1; *o*-methylacetophenone, 577-16-2; ethyl acetate, 141-78-6; 2-methylbenzoyl chloride, 933-88-0.

Photochemical Reaction between Naphthalenecarbonitriles and Dienes

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The photochemical reactions between 1- and 2-naphthalenecarbonitrile as well as 1,4-naphthalenedicarbonitrile with dienes (2,3-dimethyl-1,3-butadiene, 1,3-cyclohexadiene, 2,5-dimethyl-2,4-hexadiene, and 2,5-dimethylfuran) were examined. Different photoprocesses were observed, viz. 2 + 2 cycloaddition both across positions 1 and 2 and (formally) across positions 1 and 8a (in the latter case a secondary electrocyclic reaction leads to benzocyclooctenes as the isolated products); 2 + 2 cycloaddition at the cyano group to yield azetines, easily hydrolized to amino ketones; and 4 + 4 cycloaddition both at the substituted and the unsubstituted ring. A rationalization is offered on the basis of the charge-transfer contribution to the interaction between the partners, which favors 2 + 2 vs 4 + 4 addition.

The photochemistry of naphthalene derivatives with alkenes has been extensively investigated in the last two decades;[1] a large number of the reports involve the reactions of naphthalenecarbonitriles.[2] On the other hand, investigations of the reaction with dienes appear to be limited to the textbook case of the 4 + 4 concerted addition of naphthalene with cyclohexadiene and two hexadienes,[3] and the only report concerning naphthalenenitriles is the addition to furan.[2d,e,l] Our interest in charge-transfer and exciplex pathways in the photochemistry of aromatics[4] and the interesting results obtained in other laboratories about the photochemical reaction with dienes of other cyano- or chloro-substituted aromatics, e.g. antracene or phenanthrene derivatives,[5] prompted the present research, in which the interaction between photoexcited cyanated naphthalenes, viz. 1- and 2-naphthalenecarbonitriles (1-NN and 2-NN) and 1,4-naphthalenedicarbonitrile (NDN), with representative dienes was considered. The dienes we chose are 2,3-dimethyl-1,3-butadiene (DMB), 1,3-cyclohexadiene (CH), 2,5-dimethyl-2,4-hexadiene (DMH), and 2,5-dimethylfuran (DMFU), and the reactions were carried out in benzene or cyclohexane and, in some cases, also in a polar solvent (acetonitrile).

Table I. Photoproducts from the Irradiation of Naphthalenecarbonitriles in the Presence of Dienes

naphthalene	diene	solvent	products (% yield)
1-NN	DMB	C_6H_{12}	**1** (21), **2** (9), **3** (13), **4** (8), **5** (10), **7** + **8** (6)
	CH	C_6H_{12}	**9** (53), **10** (6), **11** (7)
	DMH	C_6H_{12}	**12** (23), **13** (20)
	DMFU	C_6H_{12}	*a*
	DMB	MeCN	**1** (23), **2** (12), **3** (b), **4** (10), **5** (b)
2-NN	DMB	C_6H_{12}	**15** (62), **16** (8)
	CH	C_6H_{12}	**17** (53), **18** (12)
	DMH	C_6H_{12}	**19** (75), **20** (5)
	DMFU	C_6H_{12}	*a*
	DMB	MeCN	**15** (60), **16** (3)
NDN	DMB	C_6H_{12}/C_6H_6	**22** (26), **24** (8)
	CH	C_6H_{12}/C_6H_6	*a*
	DMH	C_6H_{12}/C_6H_6	*a*
	DMFU	C_6H_{12}/C_6H_6	*a*

[a] The nitrile is recovered unchanged after 15 h of irradiation. [b] Present by TLC.

Results

Isolated yields of the adducts after chromatography and recrystallization are reported in Table I. GC and NMR analyses of the crude photolysates show that, while small amounts of other photoproducts are present, the identified compounds in every case account for more than 75% of converted nitriles.

Reactions of 1-NN (Scheme I). Irradiation of 1-NN in the presence of 0.1 M DMB in cyclohexane or benzene

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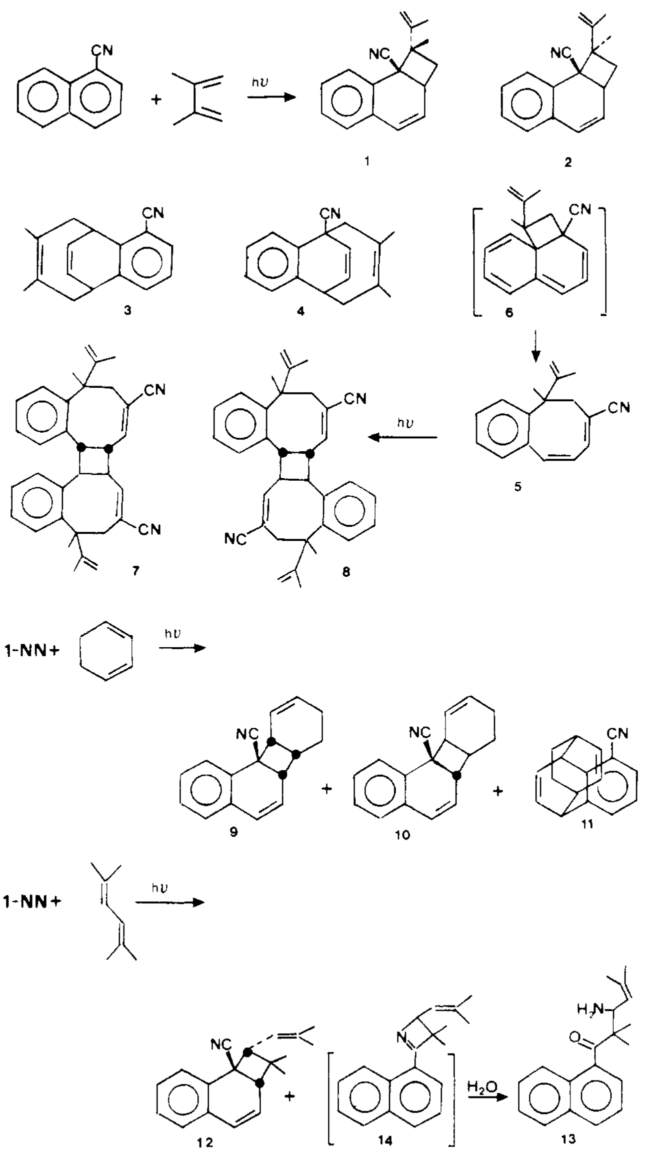
(3) Yang, N. C.; Libman, J.; Savitzky, M. *J. Am. Chem. Soc.* **1972**, *94*, 9226 and 9228.

(4) See, e.g. (a) Albini, A.; Fasani, F.; Mella, M. *J. Am. Chem. Soc.* **1986**, *108*, 4119. (b) Albini, A.; Fasani, E.; Faiardi, D. *J. Org. Chem.* **1987**, *52*, 155 and therein cited references.

(5) (a) Yang, N. C.; Srinivasachar, K.; Kim, B.; Libman, J. *J. Am. Chem. Soc.* **1975**, *97*, 5006. (b) Smothers, W. K.; Saltiel, J. *J. Am. Chem. Soc.* **1983**, *105*, 2794. (c) Yang, N. C.; Masnovi, J.; Chiang, W.; Wang, T.; Shon, H.; Yang, D. D. M. *Tetrahedron* **1981**, *37*, 3285. (d) Mizuno, K.; Pac, C.; Sakurai, H. *J. Am. Chem. Soc.* **1974**, *96*, 2993. (e) Jones, C. R.; Allman, B. J.; Mooring, A.; Spahic, B. *J. Am. Chem. Soc.* **1983**, *105*, 652.

Scheme I



yields a complex mixture of products, from which several 1 to 1 adducts were isolated and characterized. Two of these are 1,2-dihydro-1-naphthalenecarbonitriles with spectroscopic characteristics similar to the known 1-NN-alkenes 2 + 2 adducts.[2] The methine and the methylene group in the cyclobutane ring are vicinal in both cases. Thus, these are cyclobutanonaphthalenes with the same regiochemistry (structures **1** and **2**). As far as stereochemistry is concerned, the endo (and major) stereoisomer is recognized on the basis of the unusually upshifted resonance of the allylic methyl group, showing interaction with the aromatic ring in this case.

Another one of the adducts has a UV spectrum similar to benzonitrile, and the NMR spectrum shows two coupled olefinic protons, in turn coupled to two aliphatic protons absorbing at δ 3.95 and 3.75. These and other spectroscopic properties allow the assignment of structure **3**, resulting from the 4 + 4 addition of the diene onto the unsubstituted ring of 1-NN. The 4 + 4 adduct on the substituted ring is likewise obtained (product **4**), though in lower yield, and has a similar NMR spectrum.

In a fluorescing product, the UV spectrum of which shows that conjugation is more extended than in the previous cases, the arrangement PhCH=CHCH=CCN remains and the diene has added through one of the double bonds, the CH_2 group now appearing as a AB system centered at δ 3.0. A 1,2-dihydrobenzocyclooctene skeleton is in accord with spectroscopic evidence and is supported by the observed photoreactivity (vide infra). As for the regiochemistry, formula **5** is assigned to this product and is preferred to the alternative 2,2-disubstituted benzocyclooctene on the basis of the strongly different resonances observed for the protons in position 2. This is expected since one of the protons experiences the shielding effect both of the 3–4 and of the 5–6 double bonds; being very near to the latter, the other one experiences the deshielding effect of the cyano group, whereas in the other isomer inspection of the molecular model shows that the protons in position 1 sit at the same angle with the aromatic ring and thus are expected to absorb at the same field.[6] A simple rationalization is that 2 + 2 addition takes place also in this case and the primary adduct **6** undergoes electrocyclic ring opening to the eight-membered ring. A partial analogy can be drawn between product **2** and a benzocyclooctene obtained from the photoaddition between 2-NN and a vinyl ether. In that case again the reaction was rationalized as involving addition at position 1 and 8a and secondary ring opening.[2f,g]

Finally, a fraction containing two unseparated adducts in the ratio 2:1 is obtained. Their NMR spectra are almost identical and are closely related to that of compound **5**, except for the fact that there is a single olefinic absorption. Thus these are recognized as cynnamic type dimers of compound **5** and indeed are formed when the latter is irradiated in a separated experiment. Since the endo adducts would be too overcrowded, the structures of exo head-to-head and head-to-tail dimers (formula **7** and **8**) are tentatively assigned to these compounds.

Irradiation of 1-NN with CH leads again to 1 to 1 adducts. Two of the products are 1,2-cyclobutane adducts, one of them being largely predominant. On the basis of the spectroscopic properties, the analogy with the DMB reaction, and the fact that no cage dimer is formed on irradiation in the presence of xanthone, these are recognized as the endo (major) and exo adducts **9** and **10**. Another product obtained in low yield has characteristics similar to adduct **3** and is recognized as the 4 + 4 adduct **11**.

From the reaction with DMH two products were obtained. One is again a 1 to 1 adduct, and, as far as regio and stereochemistry are concerned, coupling pattern and high field absorption of the allylic methyl group support structure **12**. The second product analyzes for a 1 to 1 adduct plus one molecule of water and contains a keto and an amino group as shown by the IR spectrum. These and other spectroscopic characteristics are in accord with the structure of naphthyl ketone **13**. This product reasonably results from the hydrolysis during chromatography of the primarly formed azetine **14**, a process analogously observed during work up of similar azetines.[2k,l,7]

Irradiation of 1-NN in the presence of 0.1 M DMFU for several hours did not cause appreciable conversion of the nitrile.

Reactions of 2-NN (Scheme II). Irradiation of 2-NN in the presence of DMB yielded two 1 to 1 adducts. The most abundant one is a 1,4-dihydro-2-naphthalenecarbonitrile, and the NMR spectrum shows one olefinic proton

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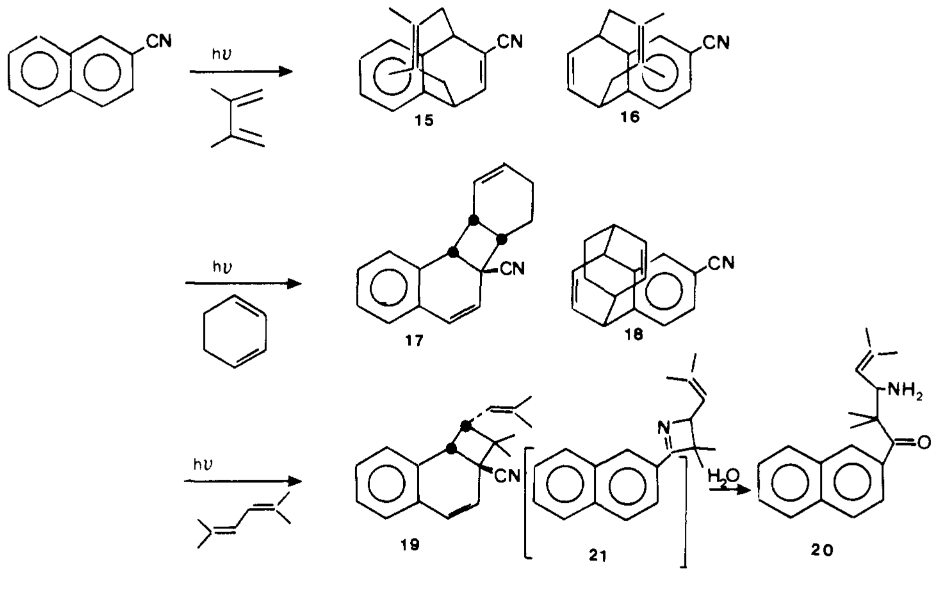
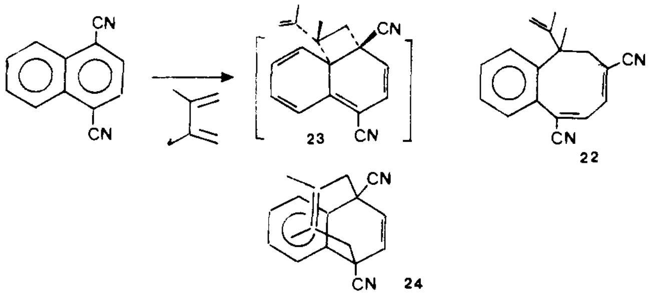
(6) In the case of the benzocyclooctene obtained from 2-NN and a vinyl ether, the regiochemistry was proposed on the basis of the observed nuclear Overhauser effect (ref 2f). In the present case, no effect is observed on irradiation of the aromatic protons, and indeed inspection of the molecular model leads to no such expectation.

(7) (a) Cantrell, T. S. *J. Am. Chem. Soc.* **1972**, *94*, 5929. (b) Cantrell, T. S. *J. Org. Chem.* **1977**, *42*, 4238.

Scheme II



Scheme III



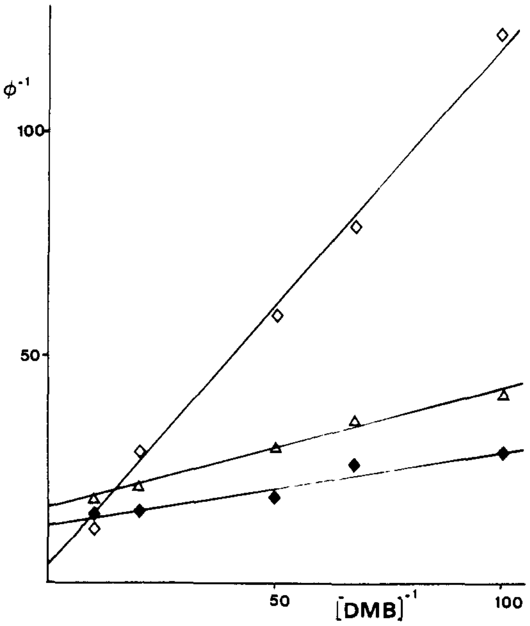


Figure 1. Double-reciprocal plot for the quantum yield of the reaction of 1-NN (◆), 2-NN (◇), and NDN (△) with DMB.

as a doublet and aliphatic signals at δ 3.37 (t), 2.97 (td), and 2.1 (m, 4 H), besides the allylic methyl groups. Thus, this product results from 4 + 4 addition onto the substituted ring (structure **15**).

The minor product shows spectroscopic characteristics similar to adduct **3** obtained from 1-NN and DMB and analogously results from 4 + 4 addition onto the unsubstituted ring (structure **16**).

The main product from the reaction of 2-NN with CH is the 2 + 2 adduct **17**, while a minor product contained in a not completely resolved chromatographic fraction shows the spectra expected for the 4 + 4 adduct **18**. The reaction with DMH leads again to a 2 + 2 adduct (structure **19**) as the main product, along with a 2-NN/DMH/H_2O adduct recognized as the aminoalkyl naphthyl ketone **20**, in turn arising from the hydrolysis of the primarily formed azetine **21**. Irradiation of 2-NN with DMFU for as long as with the other dienes resulted, as in the case of 1-NN, in no appreciable reaction of the nitrile.

Reactions of NDN (Scheme III). Photochemical reaction of NDN with DMB is slower than the corresponding reactions of 1- or 2-NN and yields two 1 to 1 adducts. The main product shows a conjugated system in the UV spectrum (λ_{max} 327 and 355); main features of the NMR spectrum are two coupled olefinic protons and an exceptionally low field aromatic proton. Only one bond of the diene participates in the reaction, and the aliphatic CH_2 group appears in the adduct at δ 4.2. All spectroscopic data are well accommodated for by structure **22**, and the effect of the cyano group in position 6 explains the deshielding of the aromatic proton in position 7. Product **22** could arise from electrocyclic rearrangement of the 2 + 2 adduct **23**. The latter and minor product is again a 1 to 1 adduct and shows four aromatic protons, two equivalent olefinic protons and two equivalent AB systems. Thus, this product arises for the 4 + 4 addition onto the substituted ring (structure **24**). Irradiation of NDN with either CH, DMH, or DMFU did not lead to appreciable nitrile conversion.

Some explorative photoreactions were carried out in acetonitrile. Nonreactive dienes, such as DMFU, again undergo no addition to the naphthalenenitriles. On the other hand, the irradiation of either 1-NN or 2-NN in the presence of DMB leads to the same results as in apolar solvents.

Discussion

The observed photochemical additions involve the singlet excited state of the naphthalenenitriles. At the concentration used in preparative experiments (0.1 M), the dienes quench a substantial fraction of the singlet state (see Table II for measured Stern Volmer constants, K_{sv}). In the case of DMB the quantum yield of reaction has been

Table II. Fluorescence Quenching and Reaction Quantum Yield in Cyclohexane

naphthalene, E_{red} (V), E_{exc} (eV)	diene, E_{ox} (V)	ΔG_{ET} (eV)	K_{sv}[a] (M^{-1})	λ_{ex},[b] nm	Φ_{lim}	K_{sv}[d] (M^{-1})
1-HN, −1.98,[e] 3.75	DMB, 1.96[f]	0.19	51		0.08	75
	CH, 1.66[f]	−0.11	104			
	DMH, 1.39[f]	−0.38	120			
	DMFU, 1.47[g]	−0.3	170	405		
2-HN, −2.13,[e] 3.68	DMB	0.41	3		0.34	2.5
	CH	0.11	97			
	DMH	−0.16	146	410		
	DMFU	−0.08	39	405		
NDN, −1.28,[e] 3.45	DMB	−0.21	46		0.06	62
	CH	−0.51	71			
	DMH	−0.78	66	480		
	DMFU	−0.7	89	460		

[a] From fluorescence quenching. [b] λ_{max} of exciplex fluorescence. [c] Limiting quantum yield of reaction. [d] From the Φ^{-1} vs $[\text{diene}]^{-1}$ plot (Figure 1). [e] Vs SCE, from ref 16. [f] Vs SCE, from ref 17. [g] Calculated from the ionization potential (8.01 V, ref 18) and the Miller relation (ref 19).

measured at different diene concentrations. From the double reciprocal plot in Figure 1 the ratio between the rates for singlet quenching and decay ($k_q/k_d = K_{sv}$) can be independently evaluated, and the values obtained (Table II) compare favorably with those arising by fluorescence quenching, thus supporting the singlet nature of the reaction. Contrary to the case of the parent molecule, in which only 4 + 4 addition is observed,[3] the interaction of the singlet state of naphthalenenitriles with dienes leads to different chemical consequences. These are (i) 4 + 4 addition (either on the substituted or on the unsubstituted ring), (ii) 2 + 2 addition (across either positions 1 and 2 or 1 and 8a), (iii) no reaction despite efficient quenching, besides, of course, (iv) 2 + 2 addition onto the cyano group.

Both observed modes of 2 + 2 addition on the ring have precedent in the photoaddition of alkenes with naphthalenenitriles.[2] Noteworthy is the regioselectivity observed in the present case (see below). A mechanistic discussion requires first that primary photoprocesses are distinguished from secondary reactions. In particular, the 2 + 2 adducts might conceivably arise from secondary Cope rearrangement of primarily formed 4 + 4 adducts, and this possibility has been verified with the parent compound.[3] In view of this fact we examined the product distribution at different conversions and the stability of the photoproducts under our conditions. In the case of the 1-NN/DMB system, as an example, both possible 4 + 4 adducts **3** and **4** are isolated and they are not transformed into the 2 + 2 adducts; actually they are only slightly decomposed on irradiation or during workup. The 2 + 2 adducts **1** and **2** are photochemically cleaved back to the starting material (as it has been already noticed[2g] for the case of the 1-NN–alkenes systems, on irradiation of stoichiometric mixtures, the percentage of 2 + 2 dimers decreases after a certain time since they form reversibly, and the percentage of the other photoproducts increases; this is not the case here, since the dienes are in large excess and overirradiation is avoided) but are not converted to other products. Products **7** and **8** are clearly secondary photoproducts from **5**. As for the benzocyclooctene **5**, its yield does increase somewhat with conversion, and although we were unable to isolate a precursor, the possibility remains that in this case a multistep mechanism is operative. Since **4** is not an intermediate, it is possible that a 4 + 2 adduct is primarily formed and undergoes sigmatropic shift to **6** and electrocyclic ring enlargement to **5**. The situation is similar in the other cases, and, except than for the amino ketones **13** and **20**, which are formed during chromatography, the other products are present before workup as well as at low conversion. Furthermore, the 1-NN/DMB and 1-NN/CH reactions were carried out also in *n*-heptane at 0 °C, concentrated, and examined at the same temperature without showing a different product distribution.

Thus, 2 + 2 additions at positions 1, 2 and 4 + 4 addition (as well as azetine formation) are independent processes, and formation of the benzocyclooctenes **5** and **21**, while possibly a multistep process, is again independent from the other ones.

In conclusion different primary processes are observed and their relative importance depends on the substrates chosen, e.g. only 4 + 4 addition from 2-NN and DMB, 2 + 2 addition both at C═C and C═N from 1-NN and DMH. This dependence and the contrast with the single mode of reaction observed with unsubstituted naphthalene (4 + 4 addition) require a rationalization, which can be reached with reference to the increasing charge transfer character of the exciplex. The calculated ΔG for electron transfer in the excited state, disregarding the ion separation energy term,[8] viz. $\Delta G_{ET} = E_{ox} - E_{red} - E_{exc}$ is reported in Table II. One can see that for each fluorophore K_{sv} increases with the exergonicity of the process and for the mononitriles reaches the diffusion-controlled limit. However, in the case of NDN, steady-state measurements yield values not higher than $k_{diff}/2$, thus pointing to a reversible quenching. A weak exciplex emission is noticed with both DMFU and (except than with 1-NN) DMH as donors.[10] Red shift with respect to monomer emission is limited with the mononitriles and more substantial with NDN, showing a significant exciplex stabilization in the latter case.

Caldwell[11] has predicted the reactivity of allowed cycloadditions by evaluating the earliness or the lateness of the crossing between the singly and doubly excited state surface through the resonance integral $\gamma(r_c) = E_T{}^A + E_T{}^B - E_S{}^A/c^2$ where E_S and E_T are the triplet and singlet energies of the addends A and B, and c^2 is the sum of the products of the coefficients of matching MO's. This model predicts that 4 + 4 cycloaddition between naphthalene and dienes is a facile process, a prediction borne out, as previously mentioned, by experiment.[3] Obviously 2 + 2 addition is much less favored since coefficients are smaller and thus the integral $\gamma(r_c)$ is higher (e.g. one calculates for

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[8] The energy for ion separation, $e^2/\epsilon\alpha$ (ref 9) is substantial in apolar solvent. However, its evaluation requires that assumptions are made with regard to the radical ions distance. We assume that the presently considered exciplexes (with the possible exception of those containing DMFU) have a similar structure, and thus a relative evaluation of ΔG_{ET} can be made disregarding the $e^2/\epsilon\alpha$ term.

[9] Rehm, D.; Weller, A. *Isr. J. Chem.* **1970**, *8*, 259.

[10] For a previous observation of the 1-NN/DMFU exciplex, see: Davidson, R. S.; Lewis, A.; Whelan, T. D. *J. Chem. Soc., Perkin Trans. 2* **1977**, 1280.

[11] Caldwell, R. A. *J. Am. Chem. Soc.* **1980**, *102*, 4004.

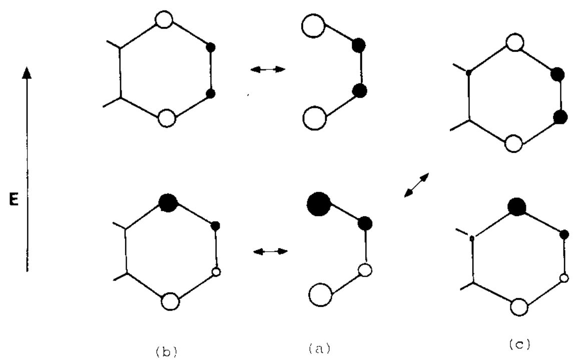


Figure 2. Frontier MO's for naphthalene (b) and butadiene (a): HOMO–HOMO and LUMO–LUMO interaction is favorable. Where an electron-withdrawing substituted naphthalene is considered (here indicated by quinoline, (c) charge transfer takes place, and the relevant interaction is between naphthalene LUMO and butadiene HOMO. The summatory of coefficient products is now zero for 4 + 4 addition and positive, although smaller than in the previous case, for 4 + 2 and possibly also for 2 + 2 addition in position 1, 2. Hückel coefficients and energies from ref 12.

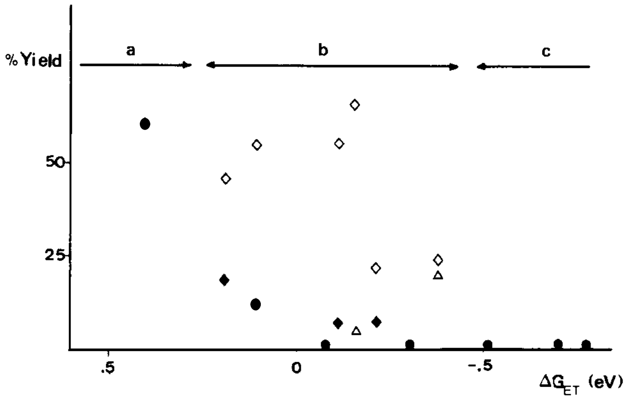


Figure 3. Percent yield of photoproducts from the reaction on naphthalenecarbonitriles and dienes and dependence on ΔG_{ET}: (◆) 4 + 4 adducts; (◇) 2 + 2 adducts on the ring; (△) adducts on the cyano group; (●) no significant reaction observed ($\Phi \ll 0.01$). In region a (no charge transfer) 4 + 4 addition predominates, in region b (some charge transfer) 2 + 2 addition on the ring predominates, in region c (complete charge transfer) no addition takes place. Previously reported[3] efficient 4 + 4 addition of parent naphthalene with dienes is further to the left in region a of this figure.

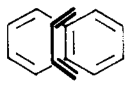
the naphthalene–butadiene system $\gamma(r_c)$ = 19.7 kcal/mol for 2 + 2 and 13.5 kcal/mol for 4 + 4 addition).[12] Cyano substitution lowers the energy of naphthalene orbitals, and thus interaction between HOMO (diene) and LUMO (naphthalene) becomes dominant. This is of course unfavorable to 4 + 4 addition (see Figure 2) due to the sign mismatch of the orbitals, whereas orbital superimposition is positive in the case of 4 + 2 and possibly also 2 + 2 addition. Furthermore, stepwise bond formation might become competitive as long as cycloaddition is more difficult. Indeed, with less reducible naphthalene derivatives and less easily oxidized dienes (e.g., 2-NN + DMB), 4 + 4 cycloaddition is dominant (region a in Figure 3), but this process is gradually replaced by 2 + 2 addition as ΔG_{ET} shifts toward negative values (region b). At $\Delta G_{ET} \leq -0.25$ eV (−5.75 kcal/mol) no significant reaction takes place (region c). This means either that electron transfer followed by the energy wasting reverse process is the main pathway in region c after interaction between excited naphthalenenitriles (NN) and dienes (D) or that the exciplex

$$NN^{1*} + D \rightarrow NN^{\bullet-} + D^{\bullet+}$$

$$NN^{\bullet-} + D^{\bullet+} \rightarrow NN + D$$

(NN···D)* is now substantially stabilized and this impedes cycloaddition in that the singly excited surface exhibits a deeper minimum in correspondance to the exciplex, and access to the pericyclic minimum on the doubly excited surface is more difficult.[13] An indication for the latter rationalization is given by the strongly red-shifted emission observed with the unreactive NDN–diene exciplexes. In any case, a charge transfer contribution lowers the efficiency of cycloaddition. Localization of the charge in the more polar DMFU complex likewise stabilizes the exciplex and favors emission but hinders chemical reaction. Literature values for the quantum yield of naphthalene cycloaddition with DMH and CH (through nonpolar exciplexes) are 0.95 and 0.23, respectively, with 1 M diene.[3] We find that Φ_{lim} decreases from 0.34 for the 2-NN/DMB cycloaddition (no charge transfer) to 0.08 and 0.06 for the 1-NN and NDN reaction with the same diene (substantial charge transfer) and is ≪0.01 for clearly exergoning transfer, e.g. NDN with CH and DMH, or when DMFU is the donor.

A further mechanistic observation is supported by the observed regio- and stereochemistry of the addition. This seems to reflect a geometry of the intermediate complex dictated by the search of maximum superimposition of the interacting systems. Thus, conformations such as **25** (leading to 4 + 4 addition) and **26** (2 + 2 addition onto positions 1 and 2) are appropriate for s-cis dienes, and conformation such as **27** (leading to 2 + 2 addition) and **28** (addition onto the cyano group, indeed observed only for DMH) for s-trans dienes. Formulation of the observed reactions as concerted cycloaddition or as involving intermediate diradicals is not univocal, in view also of the expected short lifetime of the singlet diradicals that would be involved here. Certainly in the case of the 1-NN/DMB reaction, formation of the two stereoisomeric adducts in 7:3 ratio points to a discrete intermediate, but in the other cases preference for endo addition seems to be more clear. At any rate, the preferred conformation of the initial exciplex determines, as pointed out above, the entire photochemical process. The possible role of charge transfer in photocycloaddition reactions of aromatics has been previously considered by other groups.[14] Particularly noteworthy is the recent work by Mattay,[15] showing that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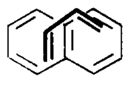
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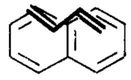
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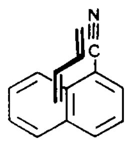

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the relative importance of the different modes of addition between benzene and alkenes depends on the value of ΔG_{ET}. The present work shows that a similar situation arises in the photoaddition between naphthalenes and dienes, with a change in product distribution as well as a decrease in quantum yield.

Experimental Section

1-NN and 2-NN were commercial products and were purified by alumina chromatography and recrystallization. NDN was prepared via the dibromide and analogously purified. Commercial pure grade dienes were redistilled before use. Spectroscopic grade solvents were used as received. NMR spectra were obtained on a Brucker 80 and 200 instruments, UV spectra on a Cary 19, IR spectra on a Perkin-Elmer 297 and mass spectra on a Du Pont DU2 instrument.

Preparative Photochemical Reactions. 1-Naphthalenecarbonitrile (1-NN) and 2,3-Dimethyl-1,3-butadiene (DMB). A solution of 1-NN (300 mg, 1.3×10^{-2} M) in 150 mL of cyclohexane was refluxed and then allowed to return to room temperature while being flushed with argon; 1.4 g (0.1 M) DMB was added, and after further a 20 min of argon purging the solution was irradiated for 10 h by means of a high-pressure mercury arc (150 W) through Pyrex while the temperature was maintained at 17 °C. Evaporation of the solvent, column chromatography over silica gel, eluting with cyclohexane and then with cyclohexane–ethyl acetate mixtures of increasing polarity, followed by a second chromatography of the main fractions with cyclohexane–benzene, 8:2, mixture yielded the following products (in order of elution).

14-Cyano-3,4-dimethyl-9,10-benzobicyclo[4.2.2]deca-3,7,9-triene (3) (60 mg, 13%): colorless needles; mp 125–27 °C (from methanol); NMR ($CDCl_3$) δ 7.15–7.5 (m, 3 H, aromatics) 6.3 (olefinic), 3.98 (1 H), and 3.55 (m, 1 H) (H-1 and H-6), 2.7 (m, 4 H, CH_2 at positions 2 and 5), 1.42 (5, 6 H); IR (KBr) 2210, 790, 755, 712 cm^{-1}. Anal. Found: C, 86.95; H, 7.35; N, 5.80. Calcd for $C_{17}H_{17}N$: C, 86.77; H, 7.28, N, 5.95.

1-Cyano-3,4-dimethyl-9,10-benzobicyclo[4.2.2]deca-3,7,9-triene (4) (74 mg, 8%): oil, impure of product **3**; NMR ($CDCl_3$) δ 7.1–7.4 (AA′BB′ system aromatics), 6.5–6.4 (olefinic protons), 3.6 (m, H-6), 2.6 (ABX system, CH_2 in 5), 2.9 (AB system, CH_2 in 2), 1.4 (s, 2 CH_3). Anal. Found: C, 86.25; H, 7.55; N, 5.60.

***endo*-1-Cyano-8-methyl-8-(2-propenyl)-2,3-benzobicyclo[4.2.0]octa-2,4-diene (1)** (97 mg, 21%): obtained as viscous oil; NMR ($CDCl_3$) δ 7.1–7.3 (m, 4 H, aromatics), 6.3 (d, J = 10 Hz, H-4), 5.87 (dd, J = 10, 5.5 Hz H-5), 4.8 and 4.9 (AB system, $=CH_2$), 3.55 (ddd, H-6), 2.5 (dd, J = 8.5, 10.5 Hz) and 2.1 (dd, J = 8.5, 10.5 Hz) (CH_2 at position 8), 1.75 (s, CH_3), 1.5 (allylic CH_3); IR (neat), 2220, 1640, 800, 780, 750 cm^{-1}. Anal. Found: C, 86.90; H, 7.35; N, 5.80.

The exo isomer 2 (41 mg, 9%): oil, impure of compound 1; NMR ($CDCl_3$) δ 7.1–7.3 (m, 4 H, aromatics) 6.3 (d, J = 10 Hz, H-4), 5.9 (dd, J = 10.6 Hz), 3.4 (ddd, H-6), 3.1 (dd) and 2.0 (dd) (CH_2 at position 8), 1.9 (s, allylic CH_3), 1.2 (s, CH_3).

Dimers 7 and 8: obtained as a viscous oil, mixture of the two (25 mg, 6%); NMR ($CDCl_3$) δ 9.5, 6.45 (H-4), 5.05 and 4.95 ($=CH_2$), 3.9 (minor isomer) and 3.47 (major isomer) (cyclobutane protons), 3.25 and 2.75 (AB system, CH_2), 1.85 (s, olefinic CH_3), 1.2 (s, CH_3). Anal. Found: C, 86.35; H, 7.30; N, 5.55.

3-Cyano-1-methyl-1-(2-propenyl)-2,3-dihydrobenzocyclooctene (5) (92 mg, 10%): colorless crystals; mp 106–108 °C (from methanol); NMR ($CDCl_3$), δ 9.5 (dd) and 7.5–8 (m) (aromatic and olefinic protons), 5 and 4.95 ($=CH_2$), 4.05 and 3.8 (AB system, methylene at position 3), 1.8 (s, allylic CH_3), and 1.7 (s, CH_3); IR (KBr) 2210, 1635, 1620, 895, 845, 768 cm^{-1}; UV (cyclohexane) λ_{max} 315 nm (log ϵ 3.7). Anal. Found: C, 86.98; H, 7.30; N, 5.90.

1-NN and 1,3-Cyclohexadiene (CH). Similar irradiation (14 h) and workup yielded the following adducts.

16-Cyano-9,10-benzotricyclo[4.2.2.2^{2,5}]dodeca-3,7,9-triene (11) (7%): obtained as viscous oil; NMR ($CDCl_3$) δ 7.1–7.3 (3 H, aromatics), 6.4 and 6.05, (2 ABXY systems, olefinic protons), 4.1 (dd), 3.8 (dd, H-1 and H-6), 3.05 (H-2 and H-5); IR (neat) 2220 cm^{-1}. Anal. Found: C, 87.65; H, 6.45; N, 5.90. Calcd for $C_{17}H_{15}N$: C, 87.51; H, 6.48; N, 6.00.

***endo*-1-Cyano-11,12-benzotricyclo[4.6.0.0^{2,7}]dodeca-3,9,11-triene (9)** (53%): mp 64–5 °C (from methanol); NMR ($CDCl_3$) δ 7–7.4 (m, 4 H, aromatics) 6.35 (dd, J = 10, 1.5 Hz, H-10), 5.1 (dd, J = 10, 5, H-9), 5.75 (center of the AB system H-3 and H-4) 3.95, (H-8), 3.75 (H-7), 3.3 (H-2), 1.5–1.7 (m, CH_2 group); IR (KBr) 2220 cm^{-1}. Anal. Found: C, 87.70; H, 6.55; N, 5.9. The exo isomer **10** (6%), obtained as an oil impure of compound **9**: NMR ($CDCl_3$) δ 6.45 (d, J = 10 Hz), 5.9 and 5.6 (H-3 and H-4), 5.7 (H-9) 3.7 (H-8), 3.2 (H-7), 2.8 (H-3). Residual double bond in the cyclohexene ring is at position 3 rather than 5 since the product does not yield a cage compound on irradiation in the presence of xanthone.

1-NN and 2,5-Dimethyl-2,4-hexadiene (DMH). After 16 h, the following adducts were obtained.

1-Cyano-8,8-dimethyl-7-(2-methylprop-1-en-1-yl)-2,3-benzobicyclo[4.2.0]octa-2,4-diene (12) (23%): colorless crystals; mp 65–7 °C (from MeOH); NMR ($CDCl_3$) δ 7.3–6.9 (4 H, aromatics), 6.4 (d, J = 10 Hz, H-4), 5.8 (dd, J = 10, 4 Hz, H-5), 3.75 (dd, J = 4, H-6) 3.7 (dd, J = 6, H-7), 5.4 (d, J = 6, CH=) 1.7, 1.75 (2 s, allylic CH_3) 1.35, 0.85 (2 s) (CH_3 groups at position 8); IR (KBr) 2220, 1662, 785, 755 cm^{-1}. Anal. Found: C, 86.75; H, 8.10; N, 5.25; Calcd for $C_{19}H_{21}N$: C, 86.64; H, 8.04; N, 5.32.

3-Amino-2,2,5-trimethyl-1-(1-naphthyl)hex-4-en-1-one (13) (20%): colorless needles; mp 105–107 °C (from cyclohexane); NMR ($CDCl_3$) δ 8.4 (dd, 1 H), 7.4–8.1 (6 H, aromatics), 4.2 (d, J = 2, H-3), 3.2 (d, J = 2, H-2), 1.8 (br s, NH_2), 1.38 (s, 6 H), 1.35 (6 H); IR (KBr) 3460, 1670 cm^{-1}. Anal. Found: C, 81.0; H, 8.25; N, 4.85. Calcd for $C_{19}H_{23}NO$: C, 81.10; H, 8.24; N, 4.98.

2-Naphthalenecarbonitrile (2-NN) and DMB. After 20 h, the following adducts were obtained.

13-Cyano-3,4-dimethyl-9,10-benzobicyclo[4.2.2]deca-3,7,9-triene (16) (8%): colorless crystals; mp 99–101 °C (from cyclohexane); NMR (C_6D_6) δ 7.2–6.6 (3 H, aromatics), 6.02 (ABY_2 system), 3.05 (2 superimposed m, bridgehead methine group), 2.35 (m, 2 CH_2), 1.3 (s, 2 CH_3); IR (KBr) 2218, 1605, 1572, 1492, 1422, 795, 740 cm^{-1}. Anal. Found: C, 86.65; H, 7.30; N, 5.85.

9-Cyano-3,4-dimethyl-7,8-benzobicyclo[4.2.2]deca-3,7,9-triene (15) (58%): colorless crystals; mp 97–100 °C (from MeOH); NMR (C_6D_6) δ 7.2–6.7 (4 h, aromatics), 6.5 (d, J = 7 Hz, H-10), 3.37 (t, J = 5, H-1), 2.97 (dt, J = 7, 5 Hz, H-6) 2.4 (m) and 2.2 (m) (2 CH_2 groups), 1.2 (s, 2 CH_3 group); IR (KBr) 2205, 1645, 1490, 1452, 1420, 900, 790, 745, 690 cm^{-1}. Anal. Found: C, 86.60; H, 7.30; N, 5.80.

2-NN and CH. After 14 h, the following adducts were obtained.

14-Cyano-9,10-benzotricyclo[4.2.2.2^{2,5}]dodeca-3,7,9-triene (16) (12%): obtained as a viscous oil; NMR ($CDCl_3$) δ 7.75 (3 H, aromatics), 6.3 and 5.95 (2 AB systems, 4 olefinic protons), 3.8 (d) and 3.55 (d) (H-1 and H-6), 3.1 (m, H-2 and H-5), 1.5–1.7 (CH_2 groups); IR (neat) 2220 cm^{-1}. Anal. Found: C, 87.55; H, 6.55; N, 5.85. No reaction on irradiation of a degassed cyclohexane solution of this compound in the presence of xanthone. Therefore **16** is presumed to have the stereochemistry shown.

1-Cyano-9,10-benzotricyclo[4.6.0.0^{2,7}]dodeca-5,9,11-triene (17) (73%): colorless crystals; mp 70–71 °C (from methanol); NMR ($CDCl_3$) δ 6.9–7.3 (3 H, aromatics), 6.55 (d, J = 10, H-11 Hz), 6 (dd) and 5.75 (m) (CH-5 and H-6), 5.65 (d, J = 10, H-12), 4.27 (d, J = 9, H-8), 3.75 (m, H-7), 2.9 (dt, H-2), 1.75 (m) and 1.3 (m) (2 CH_2 groups); IR (KBr) 2220, 1588, 870, 792 cm^{-1}. Anal. Found: C, 87.60; H, 6.50; N, 5.85.

2-NN and DMH. After 22 h, the following adducts were obtained.

6-Cyano-7,7-dimethyl-8-(2-methylpropenyl)-2,3-benzobicyclo[4.2.0]octa-2,4-diene (19) (75%): NMR ($CDCl_3$) δ 7–7.2 (4 H aromatic protons), 6.6 (d, J = 10 Hz, H-4), 5.7 (d, H-5), (5 m, vinylic H), 4.3 (d, J = 9, H-1), 3.8 (d, H-8), 1.8 and 1.55 (allylic CH_3), 1.65 and 1.5 (CH_3 groups at position 7); IR (KBr) 2220 cm^{-1}. Anal. Found: C, 86.75; H, 8.05; N, 5.20.

3-Amino-2,2,5-trimethyl-1-(2-naphthyl)hex-4-en-1-one (20) (5%): colorless crystals; mp 118 °C dec (from ligroine); NMR ($CDCl_3$) δ 8.6 (s), 7.45–8.5 (m, 6 H, aromatics), 4.52 (d, J = 2 Hz, H-4), 3.22 (d, J = 2, H-3), 2.2 (br s, NH_2), 1.35 (s, 4 CH_3 groups);

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IR (KBr) 3450, 1680 cm^{-1}. Anal. Found: C, 81.15; H, 8.35; N, 4.80.

1,4-Naphthalenedicarbonitrile (NDN) and DMB. After 16 h (solvent is now a mixture of 100 mL of cyclohexane and 50 mL of benzene), the following adducts were obtained.

1,6-Dicyano-3,4-dimethyl-7,8-benzobicyclo[4.2.2]deca-3,7,9-triene (24) (8%): colorless crystals; mp 75–78 °C (from cyclohexane); NMR (CDCl$_3$) δ 7.3–7.7 (AA'BB' system, aromatics), 6.53 (s, H-9 and H-10), 2.9 (2 identical AB systems, methylene groups), 1.45 (s, 2 CH$_3$) groups); IR (KBr) 2230, 1570, 1510, 1390, 1370, 1232, 1222, 850, 792, 750 cm^{-1}. Anal. Found: C, 83.25; H, 6.25; N, 10.60. Calcd for $C_{18}H_{16}N_2$: C, 83.04; H, 6.20; N, 10.76. Found: C, 83.25; H, 6.25; N, 10.60.

3,6-Dicyano-1-methyl-1-(2-propenyl)-2,3-dihydrobenzocyclooctene (22) (26%): colorless crystals; mp 85–7 °C (from methanol); NMR (CDCl$_3$) δ 9.65 (dd, 1 arom H), 8.3 (dd, 1 arom H), 7.7–7.9 (m, 2 arom H), 7.95 (d, J = 7.5 Hz), and 7.6 (d, H-4 and H-5), 5.2 (s, =CH$_2$), 4.2 (AB system, CH$_2$ at position 2), 1.85 (allylic CH$_3$), 1.67 (s, CH$_3$); IR (KBr) 2215, 1637, 1550, 1510, 905, 895, 832, 778, 768 cm^{-1}; UV (cyclohexane) λ_{max} 248 nm (log ϵ 4.37), 3.27 (3.9), 355 (3.85). Anal. Found: C, 82.90; H, 6.10; N, 10.65.

Other Photochemical Reactions. Irradiation of both 1-NN or 2-NN in cyclohexane in the presence of 0.1 M 2,5-dimethylfuran (DMFU) for 15 h and workup as above led to complete recovery of the nitrile. The same result was achieved from the irradiation of NDN in cyclohexane or benzene with either CH, DMH, or DMFU. Some results from the irradiation in acetonitrile are also reported in Table I.

Quantitative Measurements. Fluorescence spectra were measured by means of an Aminco-Bowman MPF spectrophotometer. Fluorescence intensities and photochemical quantum yield were measured in 1-cm optical path cells after deoxygenation by means of five freeze–degas–thaw cycles. The photochemical reaction was effected with 313-nm radiation (intensity ca. 10^{-7} Einstein min^{-1} cm^{-2}) obtained from a high-pressure mercury arc (150 W) focused through a quartz lens and filtered by means of an interference filter ($\Delta\lambda_{1/2}$ = 5 nm). Products were assayed by HPLC.

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Registry No. **1**, 116808-76-5; **2**, 116907-32-5; **3**, 116808-77-6; **4**, 116808-78-7; **5**, 116808-79-8; **7**, 116808-80-1; **8**, 116808-81-2; **9**, 116908-86-2; **10**, 116808-82-3; **11**, 116808-83-4; **12**, 116808-84-5; **13**, 116808-85-6; **15**, 116808-86-7; **16**, 116808-87-8; **17**, 116808-88-9; **18**, 116808-89-0; **19**, 116808-90-3; **20**, 116808-91-4; **22**, 116808-92-5; **24**, 116808-93-6; DMB, 513-81-5; CH, 592-57-4; DMH, 764-13-6; DMFU, 625-86-5; 1-NN, 86-53-3; 2-NN, 613-46-7; NDN, 3029-30-9.

Efficient and Versatile Synthesis of Dipeptide Isosteres Containing γ- or δ-Lactams[1]

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Independent five-step syntheses of γ- and δ-lactam-containing dipeptide isosteres, starting from the known compound, (4*S*)-3-(carbobenzyloxy)-4-(phenylmethyl)-5-oxooxazolidine (**3**), are reported. Alkylation of **3** with allyl bromide provided the corresponding 4-allyl-substituted oxazolidinone (**5**), which served as a common intermediate for each lactam series. In general terms, **5** was converted to the homologous aldehydes (**7** and **19**) by manipulating the terminal vinyl group. Reductive amination of the aldehydes with the methyl ester hydrochloride salts of L-alanine, L-phenylalanine, and L-histidine furnished the corresponding amino diesters, which were converted, by thermally induced lactam closures, to the γ- and δ-lactam-containing dipeptide isosteres in 46–59% and 32–33% respective overall yields from **3**. The resulting isosteres were diastereomeric mixtures at the lactam quaternary center. Selective deprotection was accomplished at either terminus by base hydrolysis or catalytic hydrogenolysis. A survey of standard solution phase peptide couplings revealed that addition of appropriately protected amino acid residues could be efficiently carried out at each terminus.

Considerable effort has been expended on the design and synthesis of peptide isosteres, which provide enhanced activity, selectivity, and stability to pharmacologically important peptides.[3] During the course of our work on inhibition of aspartic proteinases, we required a dipeptide isostere for the Phe-His portion of a series of compounds with the general formula 1. Our specific goal was to maintain the potency while stabilizing the Phe-His amide bond to proteolytic cleavage by the putative enzyme chymotrypsin.[4] Molecular modeling suggested that the Phe-His conformation, as depicted in Figure 1, was important for the maintenance of good binding potency. The syn-periplanar relationship between the histidine NH and the phenylalanine α-methine led us to investigate lactams 2 (eq 1) as suitable dipeptide isosteres. We were further encouraged to pursue the lactams since it is known that amide bonds which are prone to chymotrypsin cleavage are stabilized by methylation of the α-carbon or of the amide nitrogen on either side of the susceptible carboxyl moiety.[5] Both design features are incorporated into the lactam-containing dipeptide isosteres, which suggested this would be a fruitful line of investigation.

A concise synthesis that delivers a *d,l*-mixture at the quaternary lactam center (n = 2) has been recently described.[6] We, however, wished to develop a general synthesis that was capable of producing a single diastereomer

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[1] This paper is warmly dedicated to Professor Richard K. Hill on the occasion of his 60th birthday.

[2] Author to whom correspondence should be addressed.

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