Structures of Analogs of Nicotinamide–Adenine Dinucleotide. III. Crystal Structure of 1,1′-Trimethylenebisnicotinamide Dichloride Monohydrate, $(Nic^+\text{-}C_3\text{-}Nic^+)2Cl^-\cdot H_2O$[1]

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Abstract: The crystal structure of 1,1′-trimethylenebisnicotinamide dichloride monohydrate has been determined to seek information on the probable conformation of such dicationic species and to attempt to provide a structural basis for studies of spectral hyperchromism in solution. The crystals of $(C_{15}H_{18}O_2N_4^{2+})2Cl^-\cdot H_2O$ are triclinic with $a = 14.219$ (6), $b = 7.739$ (4), and $c = 7.803$ (2) Å, $\alpha = 92°7$ (3)′, $\beta = 95°26$ (2)′, and $\gamma = 92°49$ (3)′, and there are two molecules in the unit cell; the space group is $P\bar{1}$. The structure has been refined to an R factor of 0.056 on 2550 nonzero reflections collected on an automatic diffractometer (Cu Kα radiation). The conformation of the dication is quite extended although the nonhydrogen substituents on one of the C–C bonds of the trimethylene group are in the gauche rather than the fully staggered conformation. There do not appear to be any very strong inter-cation interactions as the amide groups are linked by hydrogen bonds to the chloride anions and the water molecule. The oxygen atoms of the amide groups do not participate in hydrogen bonding. The conformation found in the crystal with the pyridinium rings inclined at an angle of 120°19′ to each other and with an N(1)···N(1′) distance of 4.452 (4) Å appears not to be inconsistent with the conformation in solution that gives rise to the observed spectroscopic results.

In this laboratory, we are engaged in carrying out X-ray structural studies on a series of dinucleotide analogs where the nucleic acid bases are separated by a trimethylene bridge. Structural analyses of $(Ade\text{-}C_3\text{-}Nic)^+Br^-\cdot 3H_2O$,[3] $(AdeH\text{-}C_3\text{-}Nic)^{2+}2Br^-\cdot 2H_2O$,[4] and $Thy\text{-}C_3\text{-}Thy$[5] have been completed. While these analyses provide information on a variety of structural types, particularly in regard to the charges on the bases, some of the results were rather unanticipated. In particular, the dication $(AdeH\text{-}C_3\text{-}Nic)^{2+}$ exhibited folding of the bases in contrast to the behavior of the monocation $(Ade\text{-}C_3\text{-}Nic)^+$, which had an extended conformation.[3,4] An X-ray study of 1,1′-trimethylenebisnicotinamide dichloride monohydrate (I)[6] $(Nic\text{-}C_3\text{-}Nic)^{2+}2Cl^-\cdot H_2O$ was undertaken to try to determine whether such overlap might be a general phenomenon in dications of this type. The extent of hyperchromism (*i.e.*, increase in the transition intensity) in the series of compounds $(Nic^+\text{-}C_n\text{-}Nic^+)$ has been recently studied,[6] and it was hoped that a knowledge of the solid-state conformation of this member might help to provide a structural basis for the results obtained.

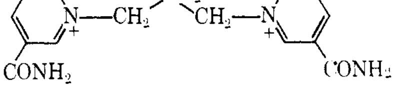
Experimental Section

The crystals of I are colorless, transparent, almost rectangular-shaped flat plates (mp 262-263° dec[6]).

Crystal data: $(C_{15}H_{18}O_2N_4^{2+})2Cl^-\cdot H_2O$, mol wt = 375.26, triclinic, $a = 14.219$ (6), $b = 7.739$ (4), and $c = 7.803$ (2) Å, $\alpha = 92°7$ (3)′, $\beta = 95°26$ (2)′, and $\gamma = 92°49$ (3)′, $V = 853.1 \times 10^{-24}$ cm^3, $D_{\text{measd}} = 1.46 \pm 0.01$ g cm^{-3}, $Z = 2$, $D_{\text{calcd}} = 1.461$ g cm^{-3}, $F(000) = 392$, μ(Cu Kα) = 36.2 cm^{-1}. No systematic absences, space group $P\bar{1}$ or $P1$, the former established by the results of the analysis. The density was measured by flotation in a mixture of cyclohexane and carbon tetrachloride and the cell data were obtained by a least-squares fit to the hand-centered settings for 12 reflections on a Picker FACS-1 diffractometer ($\lambda_{\text{CuK}\alpha} = 1.54184$ Å).

A needle-like crystal, 0.58 mm in the b direction and 0.12 × 0.07 mm in cross-section, was selected for data collection. The general procedures for data collection were as described previously,[6] with the exception that a 2°/min scan rate was used. The octants of data hkl, $hk\bar{l}$, $\bar{h}kl$, and $\bar{h}k\bar{l}$ were measured. No evidence for crystal deterioration or loss of intensity was noted. From a total of 3145 measurements, 2550 nonzero reflections were obtained using the criteria that the net count be greater than 0.075 × total background count and/or greater than 125 counts. The data were corrected for Lorentz and polarization effects but not for absorption.

The structure was solved by the symbolic addition[7] method with the aid of the programs FAME and MAGIC.[8] Full-matrix least-squares refinement varying the positional and isotropic thermal parameters for the nonhydrogen atoms and weighting all nonzero reflections equally gave an R factor of 0.154 and R_2 (defined as $[\Sigma w||F_o| - |F_c||^2/\Sigma w|F_o|^2]^{1/2}$) of 0.173. Further refinement, following introduction of anisotropic thermal parameters for the nonhydrogen atoms, gave values for R of 0.091 and R_2 of 0.127. A difference map calculated at this stage in the analysis allowed us to assign positions for all the hydrogen atoms although the two hydrogen atoms of the water molecule were not very well defined. A cycle of least-squares refinement, adjusting positional and thermal parameters for the nonhydrogen atoms and the positional parameters for the hydrogen atoms, reduced R to 0.072 and R_2 to 0.109. Some of the dimensions involving the three hydrogen atoms, H(10a), H(12a), and H(12b), and two hydrogen atoms on the water molecules, H(13a) and H(13b), were chemically unreasonable. These atoms were included, but not refined, in a further cycle of least-squares calculations at the positions obtained from the difference map. The reflections 220, $\bar{2}20$, and $\bar{3}20$ were removed from the data used in the refinement as they were judged



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[1] This work was supported by USPH Grants GM 12470 and GM 19336 and by the award of a biophysical traineeship (GM 722) to J. K. F.

[2] Alfred P. Sloan Foundation Fellow, 1968–1970.

[3] P. L. Johnson, C. A. Maier, and I. C. Paul, *J. Amer. Chem. Soc.*, **95**, 5370 (1973).

[4] P. L. Johnson, J. K. Frank, and I. C. Paul, *J. Amer. Chem. Soc.*, **95**, 5377 (1973).

[5] J. K. Frank and I. C. Paul, *J. Amer. Chem. Soc.*, **95**, 2324 (1973).

[6] J. H. Craig, P. C. Huang, T. G. Scott, and N. J. Leonard, *J. Amer. Chem. Soc.*, **94**, 5872 (1972).

[7] J. Karle and I. L. Karle, *Acta Crystallogr.*, **21**, 849 (1966).

[8] R. B. K. Dewar, Ph.D. Thesis, University of Chicago, 1968.

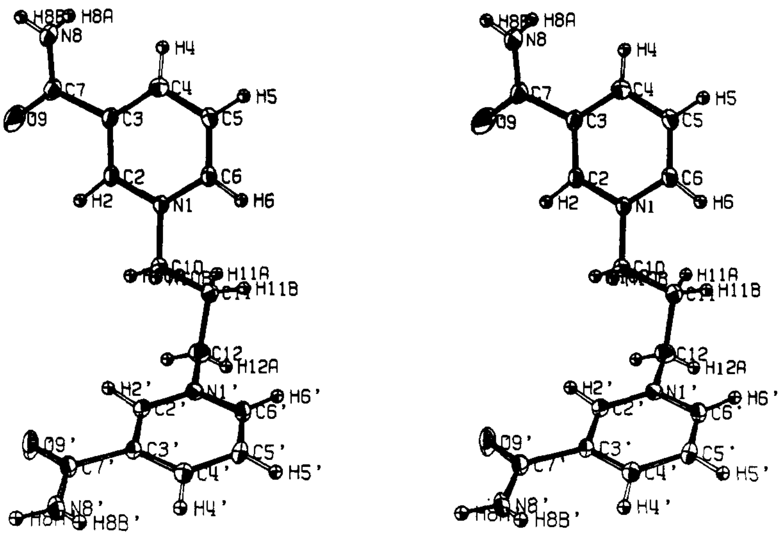

Figure 1. Stereoscopic drawing of the dication of Nic$^+$-C$_3$-Nic$^+$. The probability of the thermal ellipsoids for the nonhydrogen atoms is 37%. The hydrogen atoms are given identical arbitrary isotropic parameters.

Table I. Final Atomic Coordinates in Fractions of the Unit Cell Edge[a]

	x	*y*	*z*
Cl(1)	0.25900 (7)	0.01710 (13)	0.05736 (11)
Cl(2)	0.27333 (8)	0.47561 (14)	0.66353 (12)
N(1)	0.0966 (2)	0.7017 (4)	0.2665 (4)
C(2)	0.0560 (3)	0.7101 (5)	0.4173 (4)
C(3)	−0.0334 (3)	0.7660 (5)	0.4223 (4)
C(4)	−0.0838 (3)	0.8136 (6)	0.2716 (5)
C(5)	−0.0403 (3)	0.8038 (6)	0.1193 (5)
C(6)	0.0489 (3)	0.7509 (5)	0.1195 (5)
C(7)	−0.0706 (3)	0.7807 (5)	0.5978 (5)
N(8)	−0.1464 (3)	0.8621 (8)	0.6092 (5)
O(9)	−0.0287 (3)	0.7171 (6)	0.7191 (4)
C(10)	0.1957 (3)	0.6522 (6)	0.2705 (5)
C(11)	0.2157 (3)	0.5411 (5)	0.1150 (5)
C(12)	0.3103 (2)	0.4608 (5)	0.1442 (6)
N(1′)	0.3912 (2)	0.5919 (4)	0.1643 (4)
C(2′)	0.4319 (3)	0.6426 (5)	0.3233 (4)
C(3′)	0.5086 (2)	0.7582 (5)	0.3438 (4)
C(4′)	0.5438 (3)	0.8249 (5)	0.1987 (5)
C(5′)	0.5005 (3)	0.7729 (5)	0.0374 (5)
C(6′)	0.4245 (3)	0.6592 (5)	0.0217 (5)
C(7′)	0.5484 (3)	0.8041 (5)	0.5267 (4)
N(8′)	0.6202 (3)	0.9209 (5)	0.5523 (4)
O(9′)	0.5138 (2)	0.7310 (4)	0.6448 (3)
W(13)	0.2580 (2)	0.8835 (4)	0.6674 (4)
H(2)[b]	0.096 (3)	0.667 (5)	0.516 (6)
H(4)	−0.146 (3)	0.848 (6)	0.264 (5)
H(5)	−0.076 (3)	0.837 (6)	0.017 (6)
H(6)	0.088 (3)	0.760 (5)	0.024 (6)
H(8a)	−0.171 (4)	0.911 (7)	0.547 (6)
H(8b)	−0.169 (3)	0.887 (6)	0.694 (6)
H(10a)	0.205 (3)	0.588 (6)	0.361 (6)
H(10b)	0.232 (3)	0.770 (6)	0.282 (5)
H(11a)	0.164 (3)	0.437 (6)	0.087 (5)
H(11b)	0.212 (3)	0.596 (6)	0.010 (6)
H(12a)	0.320 (3)	0.381 (6)	0.058 (6)
H(12b)	0.317 (3)	0.387 (6)	0.247 (6)
H(2′)	0.399 (3)	0.591 (5)	0.427 (6)
H(4′)	0.601 (3)	0.885 (6)	0.210 (5)
H(5′)	0.529 (3)	0.804 (6)	−0.065 (6)
H(6′)	0.390 (3)	0.614 (6)	−0.085 (6)
H(8a′)	0.641 (3)	0.950 (6)	0.659 (6)
H(8b′)	0.642 (3)	0.982 (6)	0.485 (6)
H(13a)[c]	0.272	0.760	0.688
H(13b)[c]	0.266	0.896	0.754

[a] Standard deviations in parentheses. [b] Hydrogen atoms are given the number of the atom to which they are covalently bonded. [c] These atoms were not varied in the final cycle of refinement.

to suffer from extinction or absorption. After this cycle of refinement, *R* was 0.058 and R_2 was 0.065. Two further complete cycles of refinement, in which only the two hydrogen atoms of the water molecule were held constant, gave values of *R* and R_2 of 0.051 and 0.059, respectively. In no case was the shift of a parameter as great as one-half that of its estimated standard deviation.

The largest peak on a difference map was 0.6 electron/Å^3 positioned about 1 Å from O(9). A structure factor calculation on the unobserved data did not indicate any anomalous results. A final structure factor calculation on the data with the three reflections removed previously restored gave an *R* factor of 0.056.

The scattering curves for Cl$^-$, C, N, and O used in the analysis were taken from the compilation by Cromer and Mann;[9] that for hydrogen was that calculated by Stewart, *et al.*[10] The scattering curve for Cl$^-$ was corrected for the effects of anomalous dispersion.[11] The final positional parameters are given in Table I. The final values for the thermal parameters and the observed and calculated structure factors will appear in the microfilm edition.[12]

Results and Discussion

The conformation of the Nic$^+$-C$_3$-Nic$^+$ portion of the structure is shown in Figure 1. Bond lengths and angles are listed in Table II.

Molecular Dimensions in the Cation. The molecular dimensions of the two nicotinamide groups are remarkably similar; the greatest differences (0.04 Å in the case of the amide C–N bond) are in the amide group. The six atoms in each pyridinium ring are very close to being planar; in the case of the unprimed ring the deviations are from −0.012 to 0.006 Å, in the primed ring from −0.011 to 0.008 Å.[12] In the primed nicotinamide ring, the amide group is rotated by 2°43′ out of the plane of the ring. In the unprimed ring, the angle between the amide group and the nicotinamide ring is 11°33′. In this ring there is considerable bending of

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[9] D. T. Cromer and J. B. Mann, *Acta Crystallogr., Sect. A*, 24, 321 (1968).

[10] R. F. Stewart, E. R. Davidson, and W. T. Simpson, *J. Chem. Phys.*, 42, 3175 (1965).

[11] "International Tables for X-Ray Crystallography," Vol. III, Kynoch Press, Birmingham, England, 1962, pp 213–216.

[12] The final values for the thermal parameters, the list of *h*, *k*, *l*, $|F_o|$, and F_c, and some details of best plane calculations will appear following these pages in the microfilm edition of this volume of the journal. Single copies may be obtained from the Business Operations Office, Books and Journals Division, American Chemical Society, 1155 Sixteenth St., N.W., Washington, D. C. 20036. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche, referring to code number JACS-73-5386.

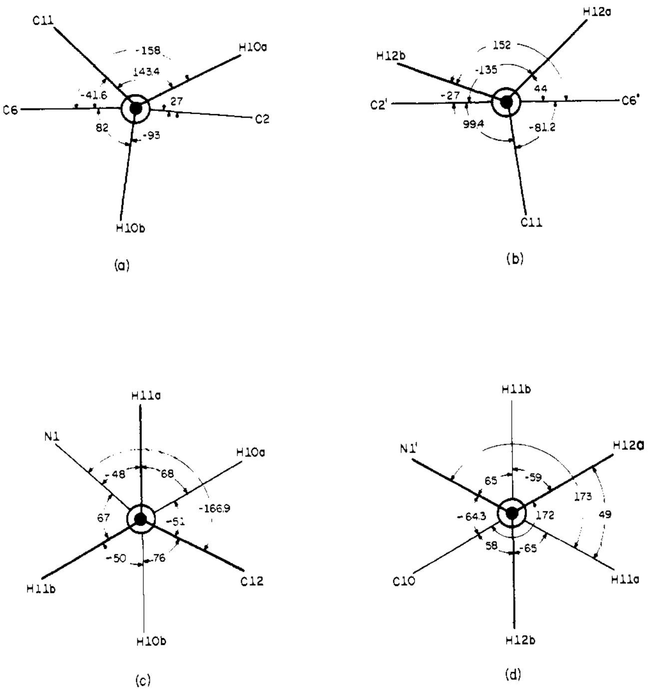

Figure 2. Torsion angles about (a) the C(10)–N(1) bond, (b) the C(12)–N(1′) bond, (c) the C(11)–C(10) bond, and (d) the C(12)–C(11) bond. Angles (ABCD) are considered positive if, when looking along the B–C bond, atom A has to be rotated clockwise to eclipse atom D.

Table II. Bond Lengths (Å)[a] and Bond Angles (deg)[b]

	Bond Lengths		
N(1)–C(2)	1.361 (5)	C(2′)–C(3′)	1.370 (5)
N(1)–C(6)	1.354 (5)	C(3′)–C(4′)	1.387 (5)
C(2)–C(3)	1.367 (5)	C(4′)–C(5′)	1.384 (5)
C(3)–C(4)	1.389 (5)	C(5′)–C(6′)	1.353 (6)
C(4)–C(5)	1.393 (6)	C(3′)–C(7′)	1.508 (5)
C(5)–C(6)	1.352 (6)	C(7′)–N(8′)	1.325 (5)
C(3)–C(7)	1.517 (5)	C(7′)–O(9′)	1.228 (5)
C(7)–N(8)	1.284 (6)	N(1)–C(10)	1.474 (5)
C(7)–O(9)	1.204 (6)	C(10)–C(11)	1.518 (6)
N(1′)–C(2′)	1.354 (5)	C(11)–C(12)	1.511 (6)
N(1′)-C(6′)	1.361 (5)	C(12)–N(1′)	1.489 (5)
	Bond Angles		
C(2)–N(1)–C(10)	118.5 (2)	C(6′)–N(1′)–C(12)	119.5 (2)
C(2)–N(1)–C(6)	119.8 (2)	N(1′)–C(2′)–C(3′)	120.9 (3)
C(6)–N(1)–C(10)	121.4 (3)	C(2′)–C(3′)–C(7′)	116.2 (3)
N(1)–C(2)–C(3)	120.8 (3)	C(4′)–C(3′)–C(7′)	124.7 (3)
C(2)–C(3)–C(7)	116.9 (3)	C(2′)–C(3′)–C(4′)	119.0 (2)
C(4)–C(3)–C(7)	123.3 (3)	C(3′)–C(4′)–C(5′)	119.2 (2)
C(2)–C(3)–C(4)	119.8 (2)	C(4′)–C(5′)–C(6′)	120.4 (3)
C(3)–C(4)–C(5)	118.2 (3)	C(5′)–C(6′)–N(1′)	120.2 (2)
C(4)–C(5)-C(6)	120.5 (3)	C(3′)–C(7′)–N(8′)	118.2 (3)
C(5)–C(6)–N(1)	120.8 (3)	C(3′)–C(7′)–O(9′)	118.9 (2)
C(3)–C(7)–N(8)	117.5 (4)	N(8′)–C(7′)–O(9′)	122.9 (4)
C(3)–C(7)–O(9)	119.5 (2)	N(1)–C(10)–C(11)	113.7 (2)
N(8)–C(7)–O(9)	123.0 (5)	C(10)–C(11)–C(12)	111.3 (3)
C(2′)–N(1′)–C(12)	120.1 (2)	C(11)–C(12)–N(1′)	112.8 (2)
C(2′)–N(1′)–C(6′)	120.3 (2)		

[a] The C–H bond lengths ranged from 0.88 to 1.05 (4) A and the N–H from 0.70 to 0.87 (5) Å. [b] The bond angles involving hydrogen atoms at C(sp^3) atoms ranged from 100 to 115° with esd from 2 to 4°. The bond angles involving hydrogen atoms at C(sp^2) atoms ranged from 113 to 127° with esd 2–3°.

the amide group out of the plane of the ring in addition to twisting; C(7) is −0.091, O(9) is 0.076, and N(8) is −0.343 Å out of the plane. In each ring, however, the four nonhydrogen atoms comprising the amide group are coplanar. The bond lengths of the amide group indicate less conjugation with the ring in the unprimed compared to the primed ring. There is a slight pyramidal distortion (0.036 Å) of N(1) from the plane defined by its three bonded neighbors, although N(1′) is effectively in the plane (−0.004 Å) of its three neighbors. Another feature of the dimensions of the cation that deserves comment is the location of the α-hydrogen atoms on the pyridine rings. The N–C–H(α) bond angles are ~10° smaller than the C–C–H(α) angles in all four cases. While steric influences due to the amide group could cause this effect in the case of H(2), no such influence is present in the case of C(3). In a similar vein, the C(2)–C(3)–C(7) angle is 116.9 (3), 116.2 (3), 116.1 (5), and 116.7 (6)° in the unprimed and primed rings of Nic$^+$-C$_3$-Nic$^+$, and in the nicotinamide rings in Ade-C$_3$-Nic$^+$ [3] and AdeH$^+$-C$_3$-Nic$^+$ [4] molecules, respectively; the corresponding values for the C(4)–C(3)–C(7) angle are 123.3 (3), 124.7 (3), 124.3 (4), and 124.4 (5)°.

Conformation of the Trimethylene Chain. The torsion angles around the four bonds comprising the trimethylene chain are shown in Figure 2. The conformation is different from those observed in other dinucleotide analogs containing the trimethylene bridge. In the fully extended Ade-C$_3$-Nic$^+$ cation,[3] the adjacent C–C bonds of the chain are oriented almost perpendicularly from the planes of the adenine and pyridinium rings, and the nonhydrogen substituents are completely staggered about the two C–C bonds of the chain. In the case of the AdeH$^+$-C$_3$-Nic$^+$ dication,[4] the C–C bonds are still approaching the perpendicular position with respect to the plane of the bases (with torsion angles of −63.3 and −61.1°), but the nonhydrogen substituents on the two C–C bonds of the chain adopt gauche orientations to each other. In Nic$^+$-C$_3$-Nic$^+$, the arrangement of the trimethylene chain with regard to the two pyridinium rings is quite different. The C(10)–C(11) bond is twisted only −41.6° from the plane of the unprimed pyridinium ring, whereas the C(12)–C(11) bond is nearly perpendicular (−81.2°) to the plane of the primed ring. Furthermore, the nonhydrogen substituents are completely staggered around the C(11)–C(10) bond but are gauche with respect to the C(12)–C(11) bond. These differences give the chain an unsymmetrical appearance in the Nic$^+$-C$_3$-Nic$^+$ cation and lead to an arrangement of the two pyridine rings that is somewhat intermediate between the overlapped and fully extended. The two nicotinamide rings make an angle of 120°19′ to each other. The distance between the centers of mass of the two pyridinium rings in the molecule is 6.660 Å and the intramolecular distance between N(1) and N(1′) is 4.452 (4) Å.

Hydrogen Bonding. The packing of molecules in the crystal is illustrated in Figure 3. The protons of the two amide groups and of the water molecule are involved in hydrogen bonding the water molecule and chloride anions. Relevant distances and angles are given in Table III. One of the hydrogen atoms bonded to N(8) forms a hydrogen bond to Cl(1$^{\mathrm{I}}$), while the other links to a water molecule, W$^{\mathrm{II}}$. Similarly, one of the hydrogen atoms on N(8′) links to Cl(1$^{\mathrm{III}}$), while the other bonds to W$^{\mathrm{IV}}$. The two hydrogen atoms of the water molecule were fixed in reasonable positions to form hydrogen bonds to two chlorine atoms, Cl(1$^{\mathrm{V}}$) and Cl(2). The geometry of this assignment is quite

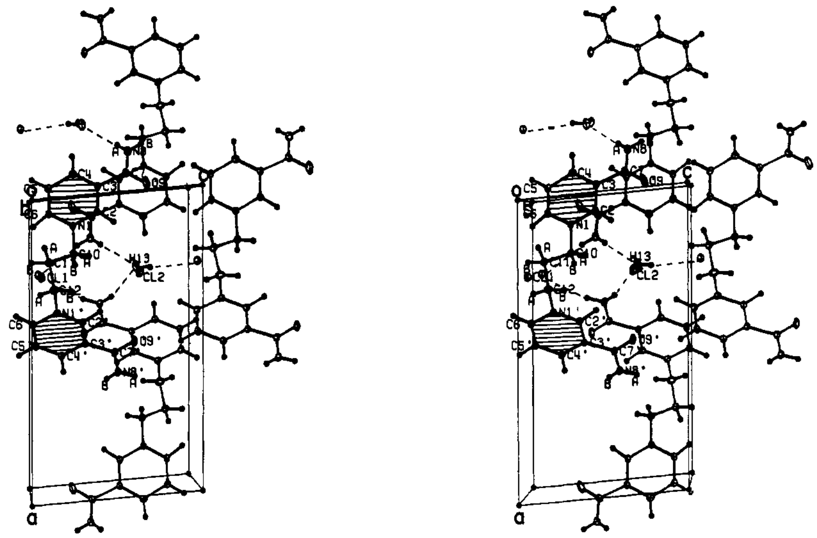

Figure 3. Stereoscopic pair showing the packing in the crystal. The basic molecule (*i.e.*, that corresponding to the coordinates listed in Table I) is shaded.

Table III. Some Details of Hydrogen Bonding[a]

Bond	Å	Angle	Deg
N(8)$\cdots$Cl(1^{I})	3.311 (4)	H(8a)–N(8)–H(8b)	103 (5)
N(8)$\cdots$W$^{\mathrm{II}}$	3.321 (6)	Cl(1^{I})$\cdots$N(8)$\cdots$W$^{\mathrm{II}}$	95.5 (1)
H(8a)$\cdots$W$^{\mathrm{II}}$	2.62 (5)	N(8)–H(8a)$\cdots$W$^{\mathrm{II}}$	175 (4)
H(8b)$\cdots$Cl(1^{I})	2.53 (5)	N(8)–H(8b)$\cdots$Cl(1^{I})	173 (4)
N(8′)$\cdots$Cl(1^{III})	3.358 (4)	H(8a′)–N(8′)–H(8b′)	113 (5)
N(8′)$\cdots$W$^{\mathrm{IV}}$	2.955 (5)	Cl(1^{III})–N(8′)–W$^{\mathrm{IV}}$	101.9 (1)
H(8a′)$\cdots$Cl(1^{III})	2.51 (5)	N(8′)–H(8a′)$\cdots$Cl(1^{III})	163 (2)
H(8b′)$\cdots$W$^{\mathrm{IV}}$	2.19 (5)	N(8′)–H(8b′)$\cdots$W$^{\mathrm{IV}}$	162 (4)
W$\cdots$Cl(1^{V})	3.176 (3)	Cl(1^{V})$\cdots$W$\cdots$Cl(2)	107.7 (1)
W$\cdots$Cl(2)	3.174 (3)	Cl(1^{V})$\cdots$W$\cdots$N(8^{II})	113.2 (1)
H(13b)$\cdots$Cl(1^{V})	2.53	Cl(1^{V})$\cdots$W$\cdots$N($8'^{\mathrm{IV}}$)	117.4 (1)
H(13a)$\cdots$Cl(2)	2.20	Cl(2)$\cdots$W$\cdots$N(8^{II})	131.4 (1)
		Cl(2)$\cdots$W$\cdots$N(8^{IV})	117.0 (1)
		N(8^{II})$\cdots$W$\cdots$N($8'^{\mathrm{IV}}$)	64.4 (1)
		H(13a)–W–H(13b)	85
		W–H(13a)$\cdots$Cl(2)	163
		W–H(13b)$\cdots$Cl(1^{V})	161

[a] I corresponds to $-x, 1-y, 1-z$; II, $-x, 2-y, 1-z$; III, $1-x, 1-y, 1-z$; IV, $1-x, 2-y, 1-z$; V, $x, 1+y, 1+z$.

reasonable both in terms of the comparison between the H–W–H and Cl(1^{V})$\cdots$W$\cdots$Cl(2) angles and the positions with respect to the hydrogen atoms from the amide groups that are donated to the water molecule. There is no inter-cation hydrogen bonding.

The oxygen atoms of the amide groups do not appear to participate in hydrogen bonding, although the distances between O(9) and H(5) in the molecule translated along the *z* direction and between O(9′) and H(5′) in the same molecule are quite short, 2.63 and 2.30 Å, respectively. The orientations of the C–H bonds with respect to the oxygen atoms, however, do not indicate hydrogen bonding. It is interesting that in none of the structures Ade-C_3-Nic$^+$, AdeH$^+$-C_3-Nic$^+$, or Nic$^+$-C_3-Nic$^+$ does the oxygen atom of a nicotinamide moiety participate in strong hydrogen bonding (there are possible C–H$\cdots$O hydrogen bonds in the Ade-C_3-Nic$^+$ and AdeH$^+$-C_3-Nic$^+$ structures). This is in marked contrast to the general behavior of simple amides[13] and of other nicotinamide analogs.[14–16]

Crystal Packing and Relation to Solution Studies. The conformation found for Nic$^+$-C_3-Nic$^+$ corresponds to a fairly extended form of the dication. It has adopted this form to effect a large separation of positive charge (4.452 (4) Å, if considered between the ring nitrogen atoms, or 6.660 Å, if considered between the centers of mass of the two rings). The dication is free to adopt such a conformation in the absence of strong intermolecular interactions, either of the stacking or hydrogen bond type. In the crystal of Ade-C_3-Nic$^+$, a still more fully extended conformation of the trimethylene chain results in a corresponding N$\cdots$N separation of 5.761 Å.[3] The conformation found in the crystal for Nic$^+$-C_3-Nic$^+$ has the amide groups arranged on the same side of the central "backbone" of the molecule. The opposite trans disposition of the two amide groups could have been achieved either by rotation around a C–N or a C–C bond in the chain. It is possible that a weak intermolecular dipole–dipole interaction between amide groups is responsible for this arrangement.

The unprimed nicotinamide ring is overlapped by the unprimed ring in the molecule at $-x, 2-y, 1-z$ (II in Table III); the amide groups lie over the pyridine rings in the related molecules (Figure 4a). Most of the atoms of one group lie approximately 3.75 Å from the plane of the other, with N(8) being the closest (3.42 Å) and O(9) being furthest away (3.84 Å); the shortest interatomic contact is 3.50 Å between N(1) and N(8^{II}). The twist of the amide group from the pyridine ring leads to fairly short contacts (3.35 and 3.43 Å) between the N(1) and C(2) in the basic molecule and O(9) in the molecule (I in Table III) at $-x, 1-y, 1-z$ (Figure 4a). The primed nicotinamide group also is in fairly close contact with a centrosymmetrically related primed ring at $1-x, 2-y, 1-z$ (IV) (Figure 4b). There is less overlap in this case although N(8′) lies almost exactly over the C(3′)–C(7′) bond. The average interplanar spacing is 3.25 Å, with N(8′)

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[13] L. Leiserowitz and G. M. J. Schmidt, *J. Chem. Soc. A*, 2372 (1969).

[14] W. B. Wright and G. S. D. King, *Acta Crystallogr.*, 7, 283 (1954).

[15] I. L. Karle, *Acta Crystallogr.*, **14**, 497 (1961).

[16] H. Hope, *Acta Crystallogr., Sect. B*, **25**, 78 (1969).

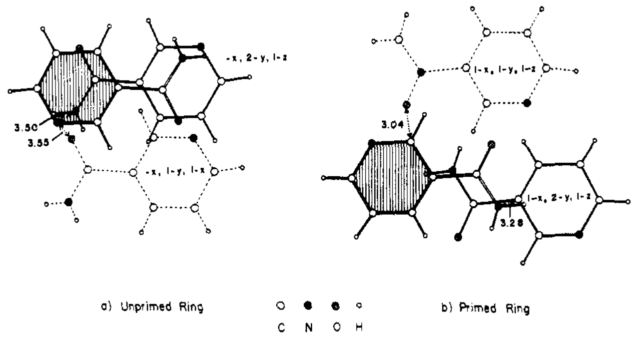

Figure 4. Drawings showing the extent of overlap among the nicotinamide groups in the structure. In each case the shaded structure corresponds to the basic molecule (*i.e.*, that whose coordinates are listed in Table I), while the molecule with the heavy bonds is "above" the plane of the basic molecule and that with dashed bonds is "below." (a) Exact projection onto the plane of the unprimed ring. (b) Exact projection onto the plane of the primed nicotinamide ring.

being closest, 3.21 Å, and O(9′) being farthest, 3.31 Å, from the plane. The shortest interatomic contact is 3.28 Å between C(3′) and N(8′^{IV}). While there is no overlap between the basic molecule and the one (III) at $1 - x$, $1 - y$, $1 - z$ (Figure 4b), there is a short contact of 3.04 Å between C(2′) and O(9′). The only other short contacts are between N(8) and N(8′) in the molecule at $-1 + x$, y, z (3.36 Å); between Cl(1) and C(10) in the molecule at x, $-1 + y$, z (3.45 Å); and between C(6′) and C(6′) in the molecule at $1 - x$, $1 - y$, $-z$ (3.38 Å).

Tinoco[17] has attempted to explain the phenomena of hypochromism (decrease in transition intensity) and hyperchromism (increase in transition intensity) on the basis of a Coulombic interaction between the induced ultraviolet electronic transition dipoles of the interacting bases. His theory predicts a hyperchromic effect in the case where the transition dipoles are collinear. However, recent studies by Craig, Huang, Scott, and Leonard[6] have suggested that in the series of compounds $\text{Nic}^+\text{-C}_n\text{-Nic}^+$, the spectroscopic results can be explained on the basis of the differences in separation of the two positive centers in a series of extended molecules. Very similar hyperchromic effects were observed for the respective members of the series $\text{Nic}^+\text{-C}_3\text{-Nic}^+$ and $\text{Nic}^+\text{-C}_3\text{-}\overset{+}{\text{N}}\text{Me}_3$. They also found that the spectroscopic results were largely independent of pH, change of solvent to ethanol, and change of anion. Our results on the $\text{Nic}^+\text{-C}_3\text{-Nic}^+$ cation would tend to support the lack of strong interaction with either solvent or anions that would stabilize a conformation other than an extended one that would presumably be favored for the isolated dication.

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[17] I. Tinoco, Jr., *J. Amer. Chem. Soc.*, 82, 4785 (1960); 83, 5047 (1961); *J. Chem. Phys.*, 33, 1332 (1960); 34, 1067 (1961).