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The Crystal Structure of Pyrazinic Acid

Fusao Takusagawa, Taiichi Higuchi, Akira Shimada,†
Chihiro Tamura,* and Yoshio Sasada**

Department of Chemistry, Faculty of Science, Osaka City University, Sugimoto-cho, Sumiyoshi-ku, Osaka 558
**Central Research Laboratories, Sankyo Co., Ltd., Hiromachi, Shinagawa-ku, Tokyo 140*
***Laboratory of Chemistry for Natural Products, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152*

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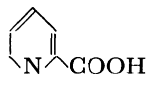
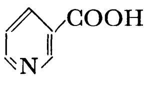
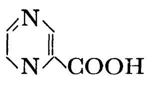
The crystal structure of pyrazinic acid has been determined by X-ray diffraction method. The crystal is orthorhombic, space group Pna2_1, $a=11.352$, $b=7.363$, $c=6.454$ Å, and $Z=4$. The structure was solved by inspecting the sharpened Patterson map. The final R value is 6.4% for all observed reflections. The molecule does not take a zwitter ion, but a neutral form. The dimensions of the pyrazine ring are close to those of pyrazine. Each molecule is joined, through the O-H···N hydrogen bond with distance of 2.669 Å, to two neighboring molecules forming the chain. These chains are linked by the weak C-H···O hydrogen bond to form the sheet parallel to the (0 0 1) plane. This hydrogen bonding scheme is quite similar to that of nicotinic acid. The hydrogen bonding type found in nicotinic acid is considered energetically favored more than that found in picolinic acid.

This work is a part of serial studies on the O-H···N hydrogen bonding in solids. The crystal structures of picolinic acid (I)[1] and nicotinic acid (II)[2] are quite different from each other. Each picolinic acid molecule is joined by two kinds of hydrogen bonds, O—H—O and N—H—N, to two neighboring molecules forming the chain. On the other hand, the O-H···N hydrogen bonds between the carboxyl group and the pyridine ring link the nicotinic acid molecules to form an endless chain.


(I)


(II)


(III)

Pyrazinic acid(III) has a similar framework and isoelectronic structure to both of (I) and (II) and hence might form either types of hydrogen bonds mentioned above. The crystal data of (III),[3] however, indicate that it is isomorphous with neither of crystals (I) nor (II). Therefore, elucidation of the effect of nitrogen atoms on the hydrogen bond formation in solids should be interesting.

Experimental

The crystals were obtained in the form of light yellow prisms by recrystallization from a mixed solution of water and ethanol. Weissenberg photographs showed that the space group is Pna2_1 or Pnam(absent spectra: $0kl$ when $k+l$ is odd, $h0l$ when h is odd). The cell dimensions were measured from zero-layer photographs taken with a double radius Weissenberg camera($R=57.296$ mm). They are given, along with other crystal data, in Table 1. One of the crystals was shaped to a sphere with an average diameter of 0.4 mm. The intensity data were collected for the 0—6 layers around the c axis and for the 0—5 layers around the b axis using the equi-inclination integrating Weissenberg technique, with Cu$K\alpha$ radiation. The intensities were estimated visually by comparison with an intensity scale; 662 independent reflections were obtained. Absorption and extinction corrections were not applied.

Table 1. Crystal data for pyrazinic acid

Molecular formula	$C_5H_4N_2O_2$
Molecular weight	124.04
Crystal system	Orthorhombic
Space group	Pna2_1
Cell dimensions:	$a=11.352\pm0.001$ Å
	$b=7.363\pm0.001$
	$c=6.454\pm0.001$
	$V=539.43$ Å^3
Z	4
Density(calcd)	1.528 g/cm^3
Density(obsd)	1.53
F(000)	256
Radiation	Cu$K\alpha$($\lambda=1.5418$ Å)
Linear absorption coefficient	12.01
Number of independent reflections	662

Structure Determination and Refinement

The structure was solved by inspecting the sharpened Patterson map. Successful solution of the structure led to assignment of Pna2_1 as the appropriate space group. All the hydrogen atoms were found in a difference Fourier map. The structural parameters of the atoms including isotropic hydrogen were refined by a full-matrix least-squares, minimizing the function $\sum w(F_o-F_c)^2$, where

$$w = 1.0/[10(|F_o|-2.0)^2 + 1.0] \quad \text{for } |F_o| \leqq 2.0$$

and

$$w = 1.0/[(|F_o|-2.0)^2 + 1.0] \quad \text{for } |F_o| \geqq 2.0$$

The final agreement factors were:

$$R = \sum|F_o-F_c|/\sum|F_o| = 0.064$$

$$R_w = [\sum w|F_o-F_c|^2/\sum w|F_o|^2]^{1/2} = 0.090.$$

The atomic scattering factors used were those listed in the International Tables for X-ray Crystallography[4] for C, N, and O atoms, and those of Stewart *et al.*[5] for H atom. The observed and calculated structure factors are listed in Table 2.*** The fractional co-

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† Deceased August 5, 1973.

*** Table 2 has been submitted to, and is kept by the office of the Chemical Society of Japan, 1-5, Kanda-Surugadai, Chiyoda-ku, Tokyo (Document No. 7412).

Table 3. The final parameters and their estimated standard deviations (in parentheses)

The coordinates of the non-hydrogen atoms have been multiplied by 10^4; those of the hydrogen atoms, by 10^3. The anisotropic thermal factors of non-hydrogen atoms are of the form of $\exp(-B_{11}h^2\cdots-B_{12}hl\cdots)$, and have been multiplied by 10^4. For the hydrogen atoms, the values are isotropic thermal factors B(Å^2).

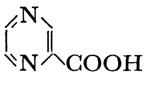
Atom	x	y	z	B_{11}	B_{22}	B_{33}	B_{12}	B_{13}	B_{23}
N(1)	4360(2)	3485(3)	0(10)	64(2)	129(4)	173(5)	8(4)	20(11)	−6(15)
C(2)	4209(2)	5288(3)	130(10)	54(2)	129(4)	108(5)	−2(4)	15(10)	−17(15)
C(3)	3091(2)	6066(4)	89(14)	52(2)	132(4)	165(6)	1(4)	39(13)	55(16)
N(4)	2119(2)	5039(3)	119(10)	53(2)	146(5)	227(7)	−10(4)	−58(11)	−60(16)
C(5)	2270(2)	3237(4)	45(11)	70(2)	138(5)	205(7)	−23(5)	9(15)	34(21)
C(6)	3385(3)	2471(4)	97(14)	73(2)	132(4)	229(7)	−15(4)	−29(14)	121(18)
C(7)	5294(2)	6434(4)	21(12)	51(2)	143(5)	145(6)	8(4)	8(11)	−102(18)
O(1)	6275(2)	5782(2)	124(13)	51(1)	143(4)	245(6)	8(3)	37(11)	54(12)
O(2)	5068(2)	8191(3)	41(10)	57(2)	115(4)	364(7)	1(3)	−21(14)	−43(18)
H(1)	301(3)	735(4)	−56(6)	2.5(7)					
H(2)	163(4)	243(5)	−46(7)	3.2(9)					
H(3)	352(3)	111(5)	59(6)	1.9(7)					
H(4)	569(4)	896(5)	69(8)	3.6(9)					

ordinates and thermal parameters are listed in Table 3.

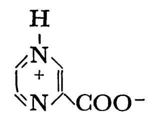
Results and Discussion

Molecular Structure. Figure 1 shows the difference Fourier map viewed along the *c* axis, in which there is no high peaks except for those due to the hydrogen atoms. Figure 2 shows the thermal ellipsoids of atoms, drawn with the 74% probability level. The bond lengths and angles are given in Fig. 3.

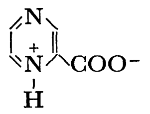
The pyrazinic acid molecule can take either of the following three forms;



(A)



(B)



(C)

From the position of the hydrogen atom in the difference Fourier map, however, it is evident that the molecule takes the neutral form (A) in the crystal. This is also concluded from the difference of 0.104(3) Å between the C(7)–O(1) and C(7)–O(2) bond lengths and the C(3)–N(4)–C(5) bond angle of 117.0(2)° (the values in parentheses denote the e.s.d.'s in the last digits).

A pyrazinic acid molecule is approximately planar with a maximum deviation of 0.044 Å, but close examination reveals that the pyrazine ring takes a chair form; the planes of C(2), N(1) and C(6) and of C(3), N(4) and C(5) make the dihedral angles of 7.2° and C(3), respectively, with the least-squares plane of C(2), 4.0°, C(5) and C(6). The least-squares planes and displacements of the atoms from them are given in Table 4.

The dimensions of the pyrazine ring are close to those of pyrazine.[7] The substitution of a carboxyl group at the C(2) atom may cause the small differences between the N(1)–C(2) and N(1)–C(6) bond lengths and between the C(2)–C(3) and C(5)–C(6) bond lengths. They are quite compatible with the difference in the π-bond orders calculated by the CNDO/2 method,[6] shown in Fig. 4. A small difference between the C(2)–N(1)–C(6) and C(3)–N(4)–C(5) bond angles may be

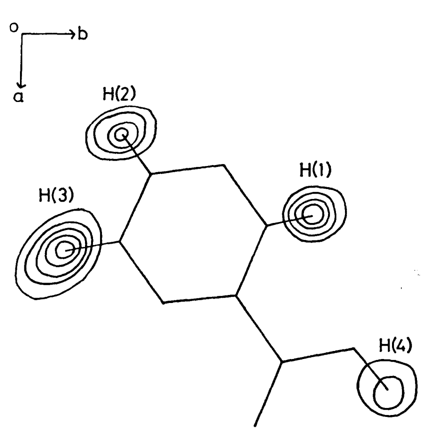


Fig. 1. A composite drawing of the electron density associated with the hydrogen atoms. The contours are at intervals of 0.1 e·Å^{-3}, beginning with the 0.2 e·Å^{-3}.

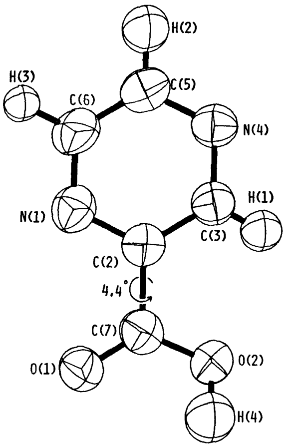


Fig. 2. The thermal ellipsoids of atoms.
The numeral indicates the dihedral angle between the planes of the pyrazine ring and the carboxyl group.

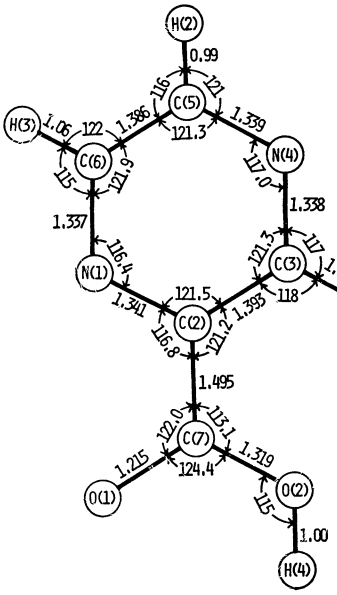


Fig. 3. Dimensions of pyrazinic acid molecule.
The estimated standard deviations are as follows: X-X=0.003~0.004 Å, X-H=0.03~0.04 Å, X-X-X=0.2°, X-X-H=2, where X and H represent the non-hydrogen atom and the hydrogen atom, respectively.

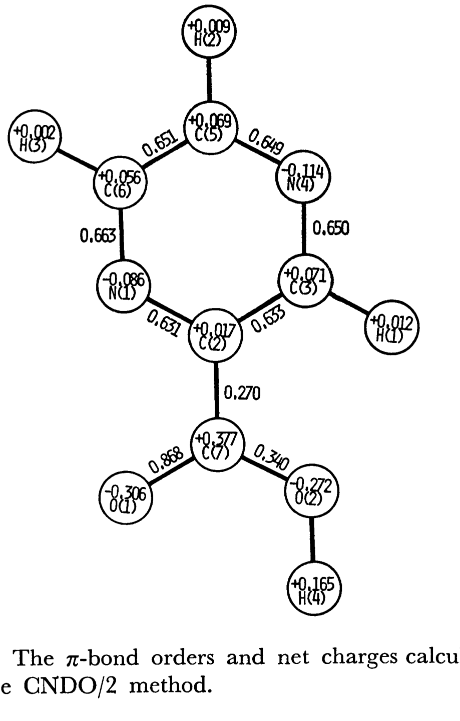


Fig. 4. The π-bond orders and net charges calculated by the CNDO/2 method.

explained by the fact that the N(4) atom participates in a hydrogen bond, while the N(1) atom does not. The 4.4(2)° difference between the N(1)–C(2)–C(7) and C(3)–C(2)–C(7) bond angles is significant judging from their estimated standard deviations. Similar differences are found in dipicolinic acid[8] and orotic acid.[9] When the hydroxyl oxygen of the carboxyl group at α-position of pyridine, pyrazine or pyrimidine ring is *s-cis* to the nitrogen atom in the ring, these two bond angles are approximately equal to each other,

TABLE 4. DEVIATIONS (Å) FROM THE LEAST-SEQUARES PLANES

Plane (I) defined by six non-hydrogen atoms of a pyrazine ring

$$0.0058X-0.0146Y+0.9999Z=0.0271$$

Plane (II) defined by four carbon atoms of a pyrazine ring

$$-0.0242X-0.0011Y+0.9997Z=-0.0342$$

where X, Y, and Z are in Å.

Atom	(I)	(II)	Atom	(I)	(II)
N(1)	−0.036	−0.088	O(1)	0.032	−0.063
C(2)	0.028	−0.002	O(2)	−0.055	−0.085
C(3)	−0.015	0.002	H(1)	−0.45	−0.42
N(4)	0.009	0.049	H(2)	−0.40	−0.31
C(5)	−0.018	−0.002	H(3)	0.37	0.32
C(6)	−0.031	0.002	H(4)	0.36	0.32
C(7)	−0.048	−0.103			

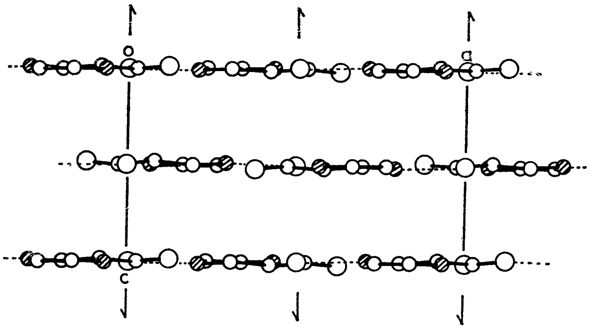


Fig. 5. A view of the crystal structure down the b axis. The hydrogen bonds are shown by broken lines.

but when it is *s-trans*, they are significantly different from each other.[1,8–11] The dihedral angle between the planes of the pyrazine ring and the carboxyl group is 4.4° and its direction is shown in Fig. 2.

Molecular Arrangement and Hydrogen-bond System. Figures 5 and 6 show the molecular arrangement viewed along the b and c axes, respectively. The molecules are arranged in layers parallel to the (001) plane with a spacing of 3.227 Å. The zig-zag chains along the c axis, consisting of the molecules linked by the O–H···N hydrogen bonds, on the same plane are joined by the weak C–H···O hydrogen bonds to form a sheet. There is no hydrogen bond between the sheets, but they are packed only by the van der Waals forces. This hydrogen bonding scheme is quite similar to that of nicotinic acid and the distance of the hydrogen bond of 2.669(3) Å is approximately equal to the 2.665 Å of nicotinic acid. Although the positions of hydrogen atoms are not determined in the crystal structure analysis of nicotinic acid, the difference between the two C–O bond lengths of the carboxyl group and the C–N–C bond angle of the pyridine ring suggest the existence of O–H···N hydrogen bond. However, the stacking of the pyrazinic acid molecule is considerably different from that of nicotinic acid, as shown in Fig. 7. There are two short contacts, 3.238(5) and 3.265(5)

TABLE 5. DISTANCES OF HYDROGEN BONDS AND SHORT CONTACTS

a) Closest contact between the layers (symmetry operation applied is given in parentheses)

Pyrazinic acid			Nicotinic acid	
N(1)···C(7)	(1−x, 1−y, 1/2+z)	3.265(5) Å	C(6)···O(2)	3.405 Å
N(1)···C(7)	(1−x, 1−y, −1/2+z)	3.238(5)	C(7)···N(4)	3.413
N(1)···O(1)	(1−x, 1−y, −1/2+z)	3.273(5)		

b) Within a layer

Pyrazinic acid		Nicotinic acid
X—H···Y	X···Y	X···Y
O(2)-H(4)···N(4)	2.669(3) Å	2.665 Å
C(3)-H(1)···O(1)	3.104(3)	3.265
C(5)-H(2)···O(1)	3.168(3)	3.259

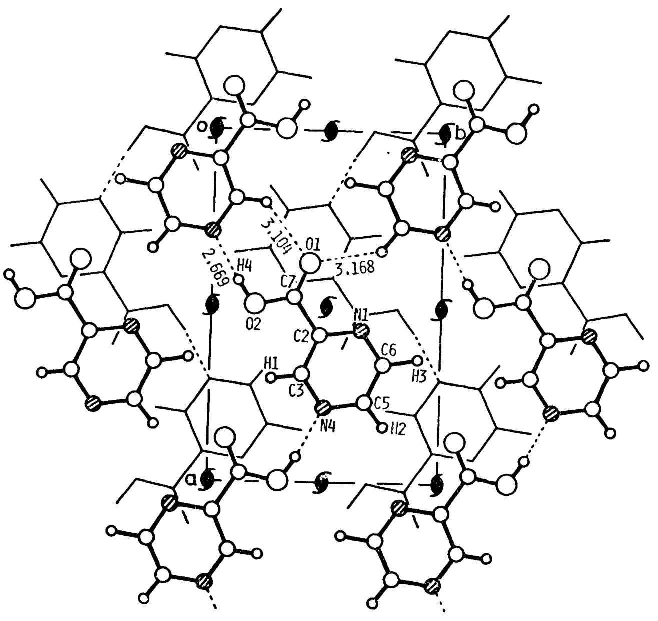
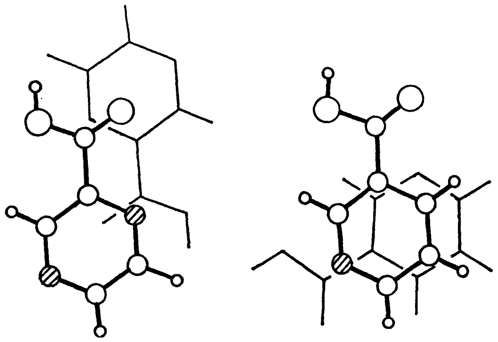


Fig. 6. A view of the crystal structure down the c axis, showing the relative orientation of the molecules in two adjacent layers parallel to the (001) plane. The hydrogen bonds are shown by broken lines.



(I) Pyrazinic acid (II) Nicotinic acid

Fig. 7. Stackings of pyrazinic acid and nicotinic acid molecules.

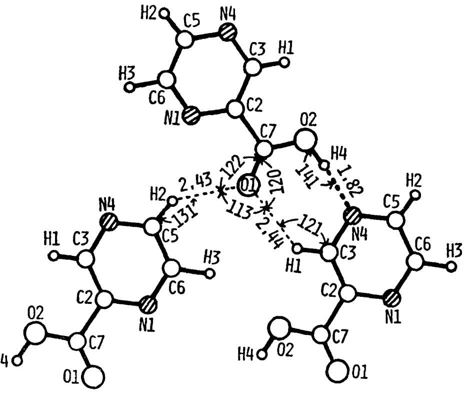


Fig. 8. Short intermolecular contacts within a molecular layer. The O-H···N and C-H···O hydrogen bonds are illustrated by heavy and thin broken lines, respectively.

Å, between the N(1) and C(7) atoms in the different sheets. The net charges on the N(1) and C(7) atoms are −0.086 and +0.377, respectively; these values indicate some electrostatic attractive-forces between them. On the other hand, nicotinic acid molecule does not contain such electronegative atom. The closest interlayer contacts of pyrazinic acid are listed, along with those of nicotinic acid, in Table 5.

As for the hydrogen bond between the carboxyl group and the nitrogen atom in the pyridine ring, the $\overset{+}{\mathrm{N}}$–H···$\overset{-}{\mathrm{O}}$ hydrogen bond is found in all the crystal structures of pyridine-carboxylic acids.[11–13] As mentioned above, hydrogen bonding types of pyrazinic acid and nicotinic acid are not the $\overset{+}{\mathrm{N}}$–H···$\overset{-}{\mathrm{O}}$, but the O–H···N. This fact may be explained as follows: The carbonyl oxygen atom O(1) is surrounded with two hydrogen atoms, H(1) and H(2), as illustrated in Fig. 8. The distances and angles are: O(1)···H(1)=2.44(4) Å, O(1)···H(2)=2.43(4) Å, C(7)=O(1)···H(1)=120(2)°, C(7)=O(1)···H(2)=122(2)°, and H(1)···O(1)···H(2)=113(5)°. These angles indicate that the H(1), H(2), O(1), and C(7) atoms are nearly on a plane. Since the O(1) atom takes the sp^2 hybrid orbitals, the two lone pairs of O(1) atom will interact with the H(1) and H(2) atoms. These may be considered as the weak C–H···O hydrogen bonds. If the H(4) atom moves from the O(2) atom to the N(4) atom, the O(1) atom no longer would take the sp^2 hybrid orbitals and the lone pairs would not be directed toward H(1) and H(2), so that the C–H···O hydrogen bonds are not formed. Therefore, the C–H···O hydrogen bond formation and protonation on the nitrogen atom are competitive. The crystal structures of pyrazinic acid and nicotinic acid suggest that the formation of the two weak C–H···O hydrogen bonds is energetically favored more than the formation of zwitter ion.

The N(4) atom takes part in the hydrogen bond, while the N(1) atom is free from it. This may be explained by the facts that the N(4) atom is more electronegative than the N(1) atom, and that the N(1) atom is shielded by the carboxyl group from the donor group for the hydrogen bond. The melting point of nicotinic acid is higher than that of picolinic acid. These two experimental facts indicate that the hydrogen bonding type found in nicotinic acid is energetically favored more than that found in picolinic acid.

Computer Programs. All the calculations were performed on a FACOM 270–30 computer at the Computer Center of Osaka City University, using the UNICS[14)] programs, SCALE(film factor, Lp and layer scaling),[15)] BOND(bond length, bond angle and least-squares plane),[16)] TE-I(thermal ellipsoid),[17)] and CNINDO (CNDO and INDO calculations).[6)]

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