[CONTRIBUTION FROM THE BUREAU OF CHEMISTRY AND SOILS, U. S. DEPARTMENT OF AGRICULTURE]

# Hydrogen Bond Formation between Hydroxyl Groups and Nitrogen Atoms in Some Organic Compounds

BY S. B. HENDRICKS, O. R. WULF, G. E. HILBERT AND U. LIDDEL

Many molecules containing hydrogen bonds between oxygen atoms have no measurable absorption in the infra-red region where characteristic OH absorption occurs in other hydroxylic compounds.[1] Such absence of absorption was used as an analytical method in our previous work. In extending that study, the question naturally arises as to what groups can take part in the formation of hydrogen bonds. The following work deals with some molecules in which a hydrogen bond if formed would be between an hydroxylic oxygen and a nitrogen atom of the type =N—.

Moore and Winmill's[2] explanation of the difference in the basicity of the tertiary and quaternary ammonium bases was that a hydrogen bond could be formed between oxygen and nitrogen atoms in the former case but not in the latter. Hydrogen bond formation was also suggested by Latimer and Rodebush[3] as an explanation for the weak basicity of ammonium hydroxide. Sidgwick[4] has reviewed this evidence and further has pointed out that nitrogen can act as a "donor," that is, form coördination compounds with appropriate groups or elements including OH. Pfeiffer and his co-workers[5] postulated hydrogen bond (partial valence) formation to explain the unusual properties of the phenylazo-1-naphthol-2.

The experimental technique and the spectroscopic procedure was the same as that described in previous work from this Laboratory.[6] However, some comment should again be made about the region 7100–7400 cm.$^{-1}$. Atmospheric water absorption lies here and makes observation difficult, so that weak absorption could be missed. The curves of Fig. 2 have been brought down to the axis of abscissa, but since the accuracy attained permits a considerable variation from zero they *must not be construed as indicating no absorption in this region* (7100–7400 cm.$^{-1}$). Very weak absorption due to presence of CH is known to lie here and there have been frequent indications of its presence in variations that were too small, at the concentrations used in this work, to be established definitely.

Compounds used were either prepared by known methods with analysis as a criterion of purity or were purified commercial products. We are indebted to Dr. T. W. J. Taylor, of Oxford University, for generous samples of 1-benzoylnaphthol-2-hydrazone and 1-benzoylnaphthol-2-acetonylhydrazone and to Dr. A. H. Blatt, of Howard University, for 2-hydroxy-5-methylbenzophenoneoxime acetate, 2-hydroxyacetophenoneoximeacetate, *cis-* and *trans*-2-hydroxybenzophenoneoximeacetates and 2,2′-dihydroxybenzophenoneoximeacetate. Drs. H. L. Haller and D. L. Vivian of the Bureau of Entomology kindly supplied us with samples of α-(β-naphthol)-2,5-dichloroazobenzene, 2,5-dichloro-2′-hydroxy-4′-methyl-5′-chloroazobenzene and 4-hydroxyazobenzene.

## Results and Discussion

Absorption in the region 6200–7500 cm.$^{-1}$ characteristic of the presence of OH groups was found to be absent for a number of compounds having configurations that would favor formation of a hydrogen bond between hydroxyl oxygen and a nitrogen atom. It was found to be present in related compounds the configurations of which excluded possible formation of such bonds. Absence of a measurable amount of such absorption thus can probably be used as a positive analytical device in detecting the presence of a hydrogen bond in this type of molecule.

Factors similar to those previously discussed as possibly affecting hydrogen bond formation between oxygen atoms are also to be considered here. One of the important requirements is that the nitrogen and oxygen atoms sharing the hydrogen bond be correctly placed, the interatomic distance, N to O, being about 2.6 Å. The ring formed should contain a minimum number of single bonds about which there could be free

---

(1) Hilbert, Wulf, Hendricks and Liddel, THIS JOURNAL, **58**, 548 (1936); *Nature*, **135**, 147 (1935); Errera and Mollet, *Compt. rend.*, **200**, 814 (1935); *J. phys. radium*, **6**, 281 (1935).

(2) Moore and Winmill, *J. Chem. Soc.*, **101**, 1635 (1912).

(3) Latimer and Rodebush, THIS JOURNAL, **42**, 1419 (1920).

(4) Sidgwick, "The Covalent Link in Chemistry," Cornell University Press, Ithaca, N. Y., 1933, p. 164.

(5) Pfeiffer, Angern, Wang, Seydel and Quehl, *J. prakt. Chem.*, **126**, 97 (1930).

(6) Wulf and Liddel, THIS JOURNAL, **57**, 1464 (1935).

rotation and the entire system should be one relatively free of strain produced by deformation of valence angles. These conditions were best met in the case of oxygen compounds by formation of six-membered rings including hydrogen, there being possibly a single example of a seven-membered ring but none of five. Other important factors are electron affinities of groups sharing hydrogen bonds and resonance phenomena, particularly those associated with a conjugate system of double bonds. Absence of discussion of resonance phenomena arises from the authors' lack of familiarity with the subject.

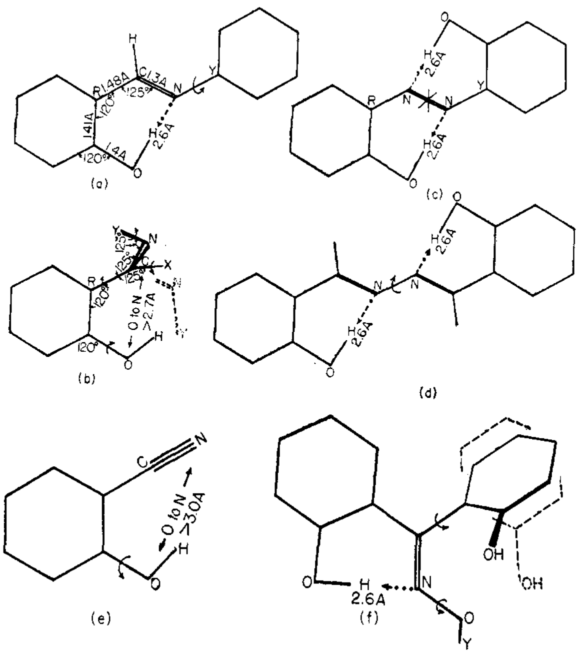


Fig. 1.—Structural formulas showing probable interatomic distances. A converging line indicates that the line departs from the plane of the figure.

Nitrogen compounds are of particular interest in that additional steric factors, arising from three rather than two directed valences, are introduced. Thus compounds R—CX=N—Y where R is unsymmetrical, can theoretically exist in two isomeric forms. Difficulty of determining their configurations by chemical methods is well recognized. The nitrogen atom of the —CX=N—Y group would be expected to have an additional coördination valence, associated with its single pair of non-binding electrons,[7] and hydrogen bond formation under otherwise favorable conditions would be possible for one isomer but not for the other. A method is thus available for absolute assignment of configuration.

The influence of the various factors mentioned above can be best studied on the ortho substituted phenols and a number of these having —CX=N—Y substituents were examined, X and Y being varied widely. Among these was salicylaldehyde-anil ($2\text{-}HOC_6H_4CH{=}NC_6H_5$), which did not give characteristic OH absorption. The probable geometrical configuration of this compound, which serves to illustrate the type, is shown as (a) in Fig. 1, the rotation of the second benzene ring (Y) about the NY bond being unknown. Formation of a hydrogen bond between the oxygen and nitrogen atoms restricts the rotation about the bond RC, the only single bond involved, and requires RCNO to be approximately coplanar with the neighboring benzene ring. Moreover the bond NY is required to have a *trans* (*anti*) configuration with respect to RC.

Presence or absence of hydroxyl absorption is used below as a criterion for determining the structures of some oximes. The methods that have been used in the past usually involved chemical transformations and thus alteration of the molecule investigated. Prominent among these are the Beckmann rearrangement and condensations presumably involving adjacent groups, such as that leading to formation of isoxazole rings, both of which are open to criticism.[8]

Absorption characteristic of the presence of OH was not observed for 2-hydroxy-5-methylbenzophenoneoxime acetate ($2\text{-}HO\text{-}5\text{-}CH_3C_6H_3C({=}NOCOCH_3)C_6H_5$, m. p. 114°) which thus must contain a hydrogen bond and have an *anti* configuration of the (—$OCOCH_3$) group with respect to the C—ROH group. Acetyl groups were introduced into this compound and most of those discussed below in order to prevent confusion arising from absorption due to the NOH group.

Since the energy of binding enhances the stability of the isomeric form having a hydrogen bond, it is not surprising to find that most such compounds have been obtained in only one form. However, Kohler and Bruce have prepared geometrical isomers of 2-hydroxybenzophenoneoxime and have shown that no evidence independent of the Beckmann rearrangement, with its corollary assumption of a *trans* shift, exists as to their

---

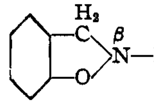
(7) N. V. Sidgwick, "The Electronic Theory of Valence," Oxford University Press, Oxford, 1929, p. 72; W. D. Kumler, This Journal, **57**, 600 (1935).

(8) A. H. Blatt, *Chem. Rev.*, **12**, 215 (1933). This review particularly clarified the subject for us and we are indebted to Dr. Blatt for further discussion and for placing his wide experience in the field at our disposal.

configurations.[9] Their "n" form of the oxime (m. p. 141–142°) was considered to have a *syn* configuration with respect to the RC bond (Fig. 1a) and was less stable thermally with respect to the isomeric "h" or *anti* oxime[7] (m. p. 142–143°). Acetates of these two compounds, namely, the *syn* acetate (m. p. 156°) and the *anti* acetate (m. p. 95°) ($2\text{-HOC}_6\text{H}_4\text{C}(=\text{NOCOCH}_3)\text{C}_6\text{H}_5$), were placed at our disposal by Dr. Blatt. The former compound gave the absorption shown in Fig. 2[10] while no measurable value was obtained for the latter. Thus a hydrogen bond is present in the *anti* acetate and this is in agreement with the configuration assigned on the basis of Meisenheimer's interpretation of the Beckmann rearrangement. A probable geometrical configuration for the *syn* acetate, which does not contain a hydrogen bond and is thus the unstable form, is shown in Fig. 1b. Spatial proximity of H and Y as in the dotted position would necessitate rotation of the CNY group about the RC bond.

Considerably less is known about the structures of the aldoximes than of the ketoximes. As might be expected the common forms, and thus probably the stable forms, that we have studied, all contain hydrogen bonds. Thus neither salicylaldoxime acetate ($2\text{-HOC}_6\text{H}_4\text{CH}(=\text{NOCOCH}_3)$) nor the 2-hydroxy-5-methylbenzophenoneoxime acetate ($5\text{-CH}_3\text{-}2\text{-HOC}_6\text{H}_3\text{C}(=\text{NOCOCH}_3)\text{C}_6\text{H}_7$) gave measurable OH absorption. Both of these compounds therefore have configurations similar to that of salicylaldehydeanil, that is, NY of $\text{R}{-}\overset{\text{H}}{\text{C}}{=}\text{N}{-}\text{Y}$ *anti* with respect to R—C. Salicylaldoxime ($2\text{HOC}_6\text{H}_4\text{CH}=\text{NOH}$) (absorption measured at 0.00333 and 0.0100 molal) was also examined and found to have the absorption shown in Fig. 2.[11] Similarity of this absorption to that of other oximes indicates that it is entirely to be accounted for by the presence of oxime OH. Chemical methods applied to studying the configuration of the aldoximes have been handicapped by lack of evidence as to whether the Beckmann rearrangement involved a *syn* or an *anti* shift, the former being assumed in the older literature. The results given above for the aldoximes, however, support the chemical findings of Brady and Bishop[12] in favor of the *anti* shift in the Beckmann rearrangement.

Salicylaldehyde α-methyl-α-phenylhydrazone ($2\text{-HOC}_6\text{H}_4\text{CH}=\text{NN}(\text{CH}_3)\text{C}_6\text{H}_5$) and salicylaldehydedimethylhydrazone ($2\text{-HOC}_6\text{H}_4\text{CH}=\text{NN}(\text{CH}_3)_2$) failed to give characteristic OH absorption. Hydrogen bond formation in these compounds probably takes place between the OH group and the β nitrogen atom, the $\text{NR}_2$ group being a variant of Y as defined above. Where the hydrogen bond is present the Y substituent must necessarily be *trans* with respect to the aromatic grouping. It is possible, however, that these results, namely, absence of measurable OH absorption in the region studied could be explained by the presence of five membered rings such as



The ordinary hydroxylic reactions of these compounds is strong evidence against this explanation.

In order further to vary the basicity of the Y group several hydrazones were studied in which NH groups were present. Salicylaldehydehydrazone ($2\text{-HOC}_6\text{H}_4\text{CH}=\text{NNH}_2$) and salicylaldehydephenylhydrazone ($2\text{-HOC}_6\text{H}_4\text{CH}=\text{NNH-C}_6\text{H}_5$) gave the absorptions shown in Fig. 2. Comparisons of these absorptions with those of analogous compounds that do not contain hydroxy groups shows that the absorptions are entirely to be accounted for by the presence of $\text{NH}_2$ or NH groups. Both compounds are thus thought to contain hydrogen bonds. In varying the substituent Y group of the hydrazone from $-\text{N}(\text{CH}_3)\text{C}_6\text{H}_5$ to $\text{NH}_2$ the limits of basicity were approximately encompassed and thus shown not to be determinative at least in this series of compounds for hydrogen bond formation.

Two substituted naphthols, 1-benzoylnaphthol-2-hydrazone ($2\text{-HOC}_{10}\text{H}_6\text{-}1\text{-CH}(=\text{NNH}_2)\text{C}_6\text{H}_5$) and 1-benzoylnaphthol-2-acetonylhydrazone ($2\text{-HOC}_{10}\text{H}_6\text{-}1\text{-C}(=\text{NN}=\text{C}(\text{CH}_3)_2)\text{C}_6\text{H}_5$) were examined. The former of these compounds[13] gave the absorption shown in Fig. 2, which should be compared with that of salicylaldehydehydrazone, the complexity of which is to be accounted for by

---

[9] Kohler and Bruce, THIS JOURNAL, 53, 1569 (1931).

[10] This absorption showed a change with temperature (60 to 20°) which is indicative of association as might be expected for this compound. Decomposition, which was not tested for, could give rise to a similar effect.

[11] The absorption of this compound showed a slight change with concentration. This is indicative of association which is well known for oximes (N. V. Sidgwick, *Ann. Reports Chem. Soc.*, **31**, 41 (1934)).

[12] Brady and Bishop, *J. Chem. Soc.*, **127**, 1357 (1925).

[13] Neither of these compounds is described in the literature. The first as supplied to us by Dr. Taylor, was recrystallized from benzene and found to have the following constants: m. p. 157°. *Anal.* (M. S. Sherman) C, 78.44; H, 5.65; N, 10.51. Calcd. C, 77.84; H, 5.39; N, 10.68.

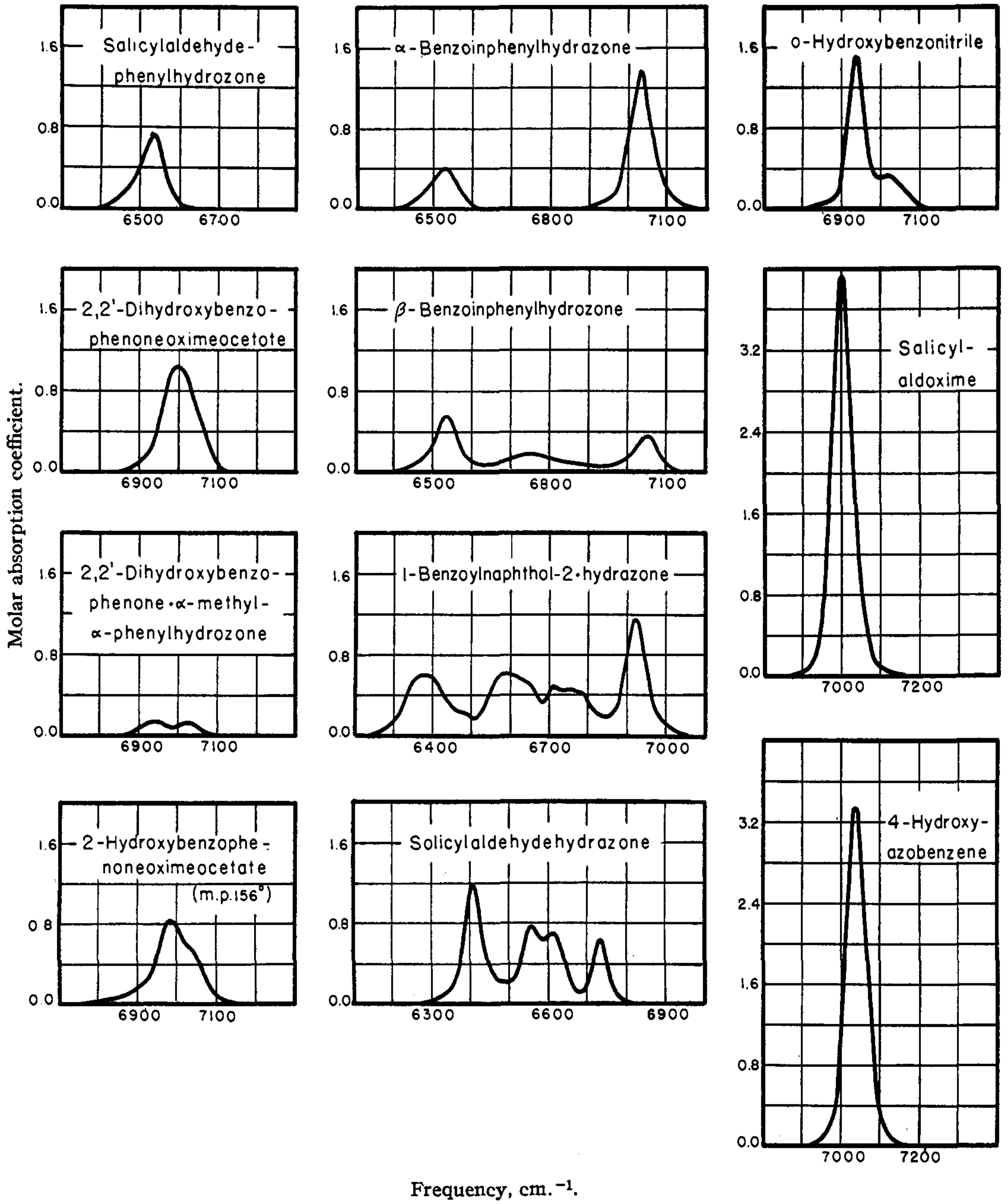
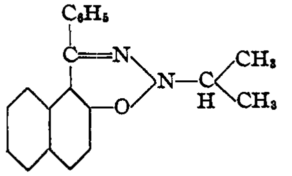
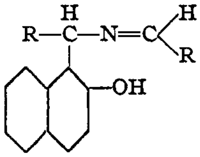


Fig. 2.—Molar absorption coefficients for some compounds of interest in the question of hydrogen-bond formation.

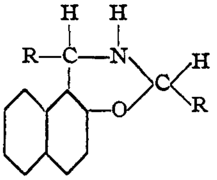
the presence of the hydrazine —$NH_2$ group. However, the absorption in the region of 7000 cm.$^{-1}$ is similar in shape and area to that found in many other phenolic compounds. It thus would seem that this substance does not contain a hydrogen bond and the possibility of ring formation through nitrogen is also eliminated. The latter compound on the other hand gave no absorption in the region studied which is of particular interest since it is derived from the hydrazone. Several explanations can be suggested for this behavior, one of which is that a six-membered ring through nitrogen



is present in the acetonyl derivative which, of course, is impossible in the case of the hydrazone. This situation is analogous to that existing in Schiff bases of the type



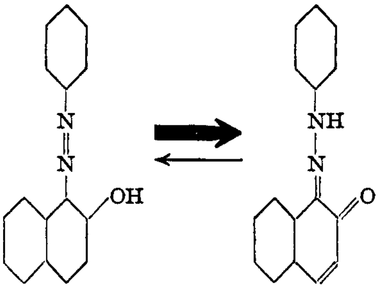
that in certain cases[14] are considered to be cyclicized as



Another possibility is that a hydrogen bond really is present in the one compound but not in the other. If this is the case it might arise from a combination of steric factors associated with an added *ortho* substituent, namely, the eight position of the naphthalene ring. Such a substituent is effective in preventing hydrogen bond formation in 2,5-dihydroxy-3,6-dibromodiethylterephthalate[1] but does not prevent it in 1-acetylnaphthol-2, a result in accord with the greater size of the bromine atom. If this explanation is correct the difference in behavior of the two naphthol derivatives probably arises from alteration of the electron affinity of the $\beta$-nitrogen atom, induced by variation of the Y group.

Characteristic OH absorption was absent for several *ortho* hydroxyazo compounds which are of the general type $R_1—N=N—R_2$. Among these were 2,5-dichlorobenzeneazo-1-naphthol-2 (2,5-$Cl_2C_6H_3N=N$-1-$C_{10}H_6OH$-2), 2,5-dichloro-2′-hydroxy-4-methyl-5′-chloroazobenzene (2,5-$Cl_2C_6H_3N=NC_6H_2OH(2)CH_3(4)Cl(5)$) and phenylazo-1-naphthol-2 (1-$C_{10}H_6OH(2)N=NC_6H_5$). In these compounds formation of five- or six-membered rings through nitrogen would require the presence of NH absorption which was not observed. Absorption due to the presence of OH in 4-hydroxyazobenzene is shown in Fig. 2 for comparison in order further to emphasize the striking departure of the hydrogen bonded compounds from normal behavior. The geometrical configurations of these compounds are probably similar to that of salicylaldehyde anil (Fig. 1) with hydrogen bonds between the hydroxylic oxygen and the $\beta$-nitrogen atom leading to six-membered rings including hydrogen. It also follows that the $R_2$ group is *trans* with respect to $R_1$ which is of particular value since chemical evidence on this point is lacking.

Presence of hydrogen bonds in the above azo compounds is further of interest in that the question of their configuration has been the subject of much discussion in the recent literature. The argument has chiefly centered upon phenylazo-1-naphthol-2 about which three discordant points of view have been held. Chemical evidence led Pfeiffer and his co-workers[5] to suggest that a hydrogen bond (partial valence) is present. Kuhn,[15] however, challenged this interpretation and suggested rather that the compound exists as a "Zwitter ion." The character of the ultraviolet absorption spectrum, however, later led Kuhn and Bär[16] to retract the earlier speculations and to interpret their results on the basis of an equilibrium between a quinoid and azo form of the molecule



the equilibrium being predominantly on the quinoid side. Burawoy,[17] who had earlier suggested, with Markowitsch,[18] a quinoid formula challenged the evidence indicative of such an equilibrium. Absence of absorption in the region studied characteristic of the presence of OH or NH definitely eliminates this third possibility. Since resonance is probably an important factor in the formation of hydrogen bonds in compounds of this type, both of the above forms possibly contribute to the stable state of the molecule.

Presence of two hydrogen bonds between oxygen and nitrogen atoms within a single molecule is indicated by the absence of OH absorption in 2,2′-dihydroxyazobenzene (2-$HOC_6H_4N=N$-$C_6H_4OH$-2) and salicylaldehydeazine (2-$HOC_6H_4$-

---

(14) Betti, *Gazz. chim. ital.*, **31**, II, 176 (1901); **33**, II, 28 (1903); Almed, Hemphill and Ray, THIS JOURNAL, **56**, 2403 (1934).

(15) Kuhn, *Naturwissenschaften*, **20**, 622 (1932).

(16) Kuhn and Bär, *Ann.*, **516**, 143 (1935).

(17) Burawoy, *ibid.*, **521**, 298 (1936).

(18) Burawoy and Markowitsch, *ibid.*, **503**, 180; 197 (1933); **504**, 71 (1933); **509**, 60 (1934).

$CH{=}NN{=}CHC_6H_4OH$-2). The geometrical requirements are interesting in both these cases but particularly so in the former which probably has the configuration shown in Fig. 1c, the atoms of the entire molecule being co-planar with a center of symmetry (x). In both compounds the R groups of R—X=N—R must have a *trans* configuration which gives a *trans trans* arrangement for salicylaldehydeazine as shown in Fig. 1d.

Factors limiting the number of hydrogen bonds to a particular atom are obscured by our general lack of understanding of the entire phenomenon. Experimental work, however, showed that at least two such bonds could form to oxygen;[1] either within a single molecule, 2,2′-dihydroxybenzophenone, or by association of two molecules, salicylic acid $(2\text{-}HOC_6H_4COOH)_2$. The steric factors introduced by the three directed valences of nitrogen unfortunately make it difficult to devise a suitable molecule for testing possible formation of two hydrogen bonds to a single nitrogen atom within a molecule. Examination of 2,2′-dihydroxybenzophenoneoxime acetate $(2\text{-}HOC_6H_4C({=}NOCOCH_3)C_6H_4OH\text{-}2)$ and 2,2′-dihydroxybenzophenone-α-methyl-α-phenylhydrazone $(2\text{-}HOC_6H_4C({=}NNCH(C_6H_5))C_6H_4\text{-}OH\text{-}2)$ showed that both compounds gave absorptions that probably are to be associated with the presence of OH groups (Fig. 2). For neither substance, however, does the molal absorption exceed that given by normal phenolic compounds containing single OH groups and that of the latter compound is extremely low. If a hydrogen bond is formed in 2,2′-dihydroxybenzophenoneoxime acetate, then the geometry of the molecule is probably that shown in Fig. 1f, the ring $R_2$ being forced out of the plane of the figure by the proximity of the $—OCOCH_3$ group. Thus the molecule has a configuration similar to both the *syn* and *anti* forms of 2-hydroxybenzophenoneoxime acetate and would be expected to give an absorption similar to that of the non-hydrogen bonded form of this latter substance as was observed. The absorption of the α-methyl-α-phenylhydrazone derivative on the other hand is much less than that of the oxime acetate. This is possibly to be associated with the fact that while one of the $—C_6H_3OH(R)$ groups must be *syn* with respect to the $R_2(—NCH_3C_6H_5)$ substituent of $R_1—C{=}N—R_2$ the other can tend to form a hydrogen bond with the α nitrogen atom. The weak absorption naturally brings up the question of the limit dividing hydrogen bonded from non-hydrogen bonded compounds or possible gradations from one extreme to the other. The body of experimental evidence is not yet sufficient to permit of reasonable discussion of this point.

Measurements were made on a number of compounds in which hydrogen bond formation was not particularly expected. Among these was 2-hydroxybenzonitrile $(2\text{-}HOC_6H_4CN)$ and this gave OH absorption as shown in Fig. 2. In this compound the nitrogen atom of the $—C{\equiv}N$ group, note Fig. 1e, is so far from the OH group as to make impossible hydrogen bond formation within the molecule. Absorptions given by α- (m. p. 155°) and β- (m. p. 106°) benzoinphenylhydrazones are shown in Fig. 2. These compounds give absorptions near 6600 cm.$^{-1}$ which is to be expected from the presence of NH groups. However, additional absorption between 6600 and 7100 cm.$^{-1}$ is probably due to the presence of OH groups. Results obtained from α- and β-benzoinoxime acetates[1] and from 8-hydroxyquinoline[6] have been published previously. While all these compounds show complex absorption which is worthy of further analysis, it is sufficient for the present purpose to point out that they give considerable absorption in the OH region. A hydrogen bond to a nitrogen atom forming a five-membered ring including hydrogen is possible for all these compounds but apparently is not present in any of them.

## Summary

Presence of hydrogen bonds in a number of *ortho* hydroxy aromatic compounds of the general type $2\text{-}HOC_6H_4X{=}NY$, where X is nitrogen or carbon, and Y is carbon, nitrogen or oxygen was indicated by absence of infrared absorption associated with presence of hydroxyl groups. Formation of hydrogen bonds requires the $HOC_6H_4$ group to have a *trans* configuration with respect to Y and this is true for the oximes, hydrazones, substituted imides and azo compounds that were studied.

Washington, D. C. Received July 20, 1936