[Chem. Pharm. Bull. 26(1) 127—134 (1978)]

UDC 547.789.6.04.08 : 543.424.06

Studies on Benzothiazole Derivatives as Chelating Agents. IV.[1] Coordination to Divalent Metal Ions

Naoki Shimidzu and Toyozo Uno

Faculty of Pharmaceutical Sciences, Kyoto University[2]

(Received May 27, 1977)

The coordination of the benzothiazole derivatives to divalent metal ions in solutions were examined by their absorption and resonance Raman spectra, and the comparison of the reactivities of the structurally related compounds with metal ions. In the solid state it was also investigated by the infrared spectrum and the magnetic susceptibility. Both in the solid state and in solutions, the benzothiazole derivatives behave as terdentate chelating agents with divalent metal ions and coordinate to the metal ions through the phenolic OH and the nitrogen atoms of the thiazole ring and the azo or azomethine group. The copper chelate has a plane structure in the molar ratio of 1 : 1 ligand-to-metal and an octahedron structure in 2 : 1, similarly to the nickel and the zinc chelates. The azo-hydrazone tautomerism of the benzothiazolylazo derivatives was also discussed.

Keywords——benzothiazole derivatives; terdentate chelating agent; coordination to metal ions; resonance Raman spectrum; infrared spectrum; magnetic moment; azo-hydrazone tautomerism

In the preceding paper[1] the acid–base equilibria of the benzothiazole derivatives and their chelate formation with metal ions were investigated potentiometrically. In this study, the coordination of the benzothiazole derivatives to divalent metal ions in solutions was examined by their absorption and resonance Raman spectra along with the azo-hydrazone tautomerism of the azo derivatives. In the solid state they were also examined by the infrared (IR) spectra and the magnetic susceptibility.

Experimental

Reagents——The benzothiazole derivatives listed with the abbreviations in Table I were used. The syntheses of these ligands were described in the previous paper.[3]

Apparatus——The absorption spectra were observed using a Hitachi recording spectrophotometer model EPS-2U. The resonance Raman spectra were recorded on a JEOL S-1 laser Raman spectrophotometer with the excitation lines 488.0 and 514.5 nm of a Coherent 52G Ar^+ laser (2W). The infrared spectra were measured using a Koken DS 301 or a JASCO IRA-2 infrared spectrophotometer for Nujol mulls.

Magnetic Moment——The magnetic susceptibility of the metal chelate was obtained by Gouy's method and calculated using the following equation with the correction of the diamagnetism of the ligand.

$$\mu_{\text{eff.}} = 2.83\sqrt{\chi_M \cdot T}$$

where χ_M is molar susceptibility and T is absolute temperature.

Preparation of Metal Chelates——$Zn(NS4ABT)_2$: To a solution of NS4ABT in acetone was added a solution of $Zn(CH_3COO)_2 \cdot 2H_2O$ in acetone. The precipitate was filtered off and recrystallized from pyridine. Yellow needles. *Anal.* Calcd. for $Zn(C_{14}H_9N_2OS)_2$: C, 58.80; H, 3.17; N, 9.80; Zn, 11.43. Found: C, 59.01; H, 3.06; N, 9.47; Zn, 11.31.

$Ni[1(2BTA)2NT]_2$: To a solution of 1(2BTA)2NT (290 mg) in acetone was added an excess of $NiCl_2 \cdot 6H_2O$ in water. The solution was made alkaline with KOH and permitted to stand until the brown precipitation (250 mg) was occurred. *Anal.* Calcd. for $Ni(C_{17}H_{10}N_3OS)_2$: C, 61.19; H, 3.02; N, 12.59. Found: C, 61.49; H, 3.02; N, 12.38.

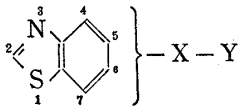
1) Part III: N. Shimidzu and T. Uno, *Chem. Pharm. Bull.* (Tokyo), **25**, 2942 (1977).
2) Location: *Yoshidashimoadachi-cho, Sakyo-ku, Kyoto.*
3) N. Shimidzu and T. Uno, *Chem. Pharm. Bull.* (Tokyo), **21**, 184 (1973).

Ni[2(4BTA)4MePh]$_2$: This was synthesized in the same procedure as the preparation of Ni[1(2BTA)-2NT]$_2$ and recrystallized from aqueous methanol to yield purple red crystals. *Anal.* Calcd. for Ni($C_{14}H_{10}N_3O_2S$)$_2$: C, 53.61; H, 3.21; N, 13.40. Found: C, 53.52; H, 3.12; N, 13.20.

The content of zinc was determined by chelatometric titration.[4] The deuterated compounds were obtained by usual exchange reaction with C_2H_5OD.

Table I. Benzothiazole Derivatives and Their Abbreviations

Compound	Abbreviation	X[a]	Y[a]
N-Salicylidene-2-aminobenzothiazole	NS2ABT	–N=CH–	C_6H_5OH
2-(2-Benzothiazolylazo)-4-methoxyphenol	2(2BTA)4MePh	–N=N–	$C_6H_4OHOCH_3$
1-(2-Benzothiazolylazo)-2-naphthol	1(2BTA)2NT	–N=N–	$C_{10}H_6OH$
2-(*o*-Hydroxyphenylimino)-methylbenzothiazole	2(HPI)MBT	–CH=N–	C_6H_5OH
N-Salicylidene-4-aminobenzothiazole	NS4ABT	–N=CH–	C_6H_5OH
2-(4-Benzothiazolylazo)-4-methoxyphenol	2(4BTA)4MePh	–N=N–	$C_6H_4OHOCH_3$
1-(4-Benzothiazolylazo)-2-naphthol	1(4BTA)2NT	–N=N–	$C_{10}H_6OH$
2-(7-Benzothiazolylazo)-4-methoxyphenol	2(7BTA)4MePh	–N=N–	$C_6H_4OHOCH_3$

a) 

Results and Discussion

Figure 1 shows the absorption spectra of 2(2BTA)4MePh and its metal chelates, as an example. The spectrum of the nickel chelate is similar to that of the cadmium chelate and the wavelength of their absorption maxima does not shift as the pH value in solution changes from neutral to alkaline. On the other hand, the spectrum of the copper chelate has a maximum at 660 nm in an acid region in the solution of molar ratio of both 1: 1 and 2: 1 ligand-to-metal, though their absorption intensities are different. However, in an alkaline region

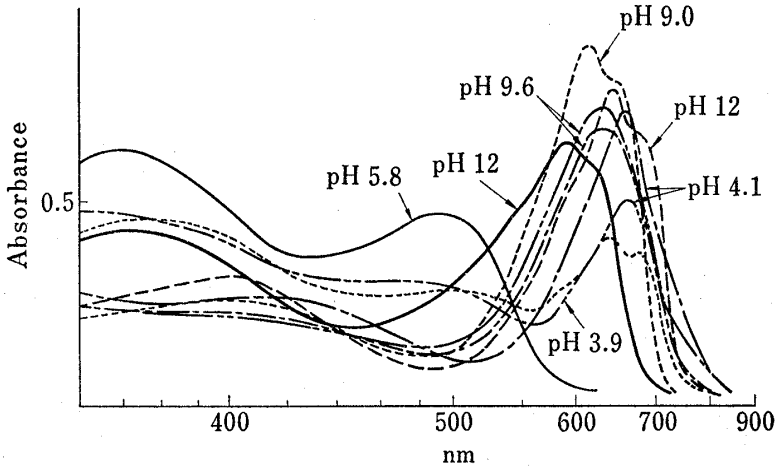


Fig. 1. Absorption Spectra of 2(2BTA)4MePh and Its Metal Chelates in 2/1(v/v) Dioxane/Water Solution

Conc. of Ligand: 4×10^{-5} M.
————, ligand.
————, nickel chelate (ligand: $Ni^{2+}=2:1$).
————, cadmiun chelate (ligand: $Cd^{2+}=2:1$).
————, copper chelate (ligand: $Cu^{2+}=1:1$).
————, copper chelate (ligand: $Cu^{2+}=2:1$).

4) K. Ueno, "Kireito Tekiteiho," Nankodo Co., Ltd., Tokyo, 1960.

their absorption maxima change to 630 nm, but their intensities do not differ too greatly. The results derived from these spectral features are analogous to the results obtained potentiometrically[1]; the benzothiazole derivatives react with copper to form the chelates of 1: 1 ligand-to-metal in an acid region and of 2: 1 in an alkaline region, while they react with the other metal ions, such as nickel and cadmium, to form a 2: 1 chelate.

The manner in the coordination of 2-substituted benzothiazole derivatives to metal ions may be estimated by the comparison of the reactivity of NS2ABT, 2(HPI)MBT and 2-azo compounds with metal ions. As described in the previous paper,[3] 2(HPI)MBT has the greater reactivity with metal ions as compared with NS2ABT; NS2ABT is poor in the reactivity with metal ions, but 2(HPI)MBT reacts with divalent metal ions to produce red colored complexes. This may be attributed to the formation of the condensed rings as a result of the terdentate ligand, including the coordination from the thiazole ring. With respect to the coordination of the azo group of 4-(2-pyridylazo)-resorcinol (PAR), Geary *et al.*, by comparing the color reactions of PAR and some structurally related compounds concluded that the nitrogen atom farthest from the pyridine ring made the greater contribution.[5] Because 2-azo compounds, 2(HPI)MBT and NS2ABT seem to be structurally comparable with PAR

Table II. Frequencies of the Strongest Resonance Raman Band under 1450 cm^{-1}

Compound	Undissociated	Dissociated	Metal chelate
2(2BTA)4MePh	1391	1330	—1280
1(2BTA)2NT	1375	1195	—1335
2(4BTA)4MePh	1400	1340	1343—1355
1(4BTA)2NT	1225	1203	—1345
2(7BTA)4MePh	1398		

and its related compounds, above considerations are probably applicable concerning to the coordination of the azo group of 2-azo compounds and hence the nitrogen atom farthest from the thiazole ring may contribute to the coordination.

The benzothiazolylazo derivatives show absorption maxima in the spectral region around 500 nm, where two intense excitation lines, 488.0 and 514.5 nm, are available from the Ar^+ laser and rigorous resonances with high sensitivities are expected even at very low concentrations. As described in the preceding paper,[1] an azo-hydrazone tautomerism is present with the benzothiazolylazo derivatives. Machida *et al.* investigated the resonance Raman spectra of *p*-aminoazobenzene-type acid–base indicators at various pH and assigned the characteristic Raman frequencies of the azo- and hydrazone-structures.[6] The resonance Raman spectra of the benzothiazolylazo derivatives and their metal chelates were measured in order to obtain the information on the structure of the metal chelates and azo-hydrazone tautomerism. Table

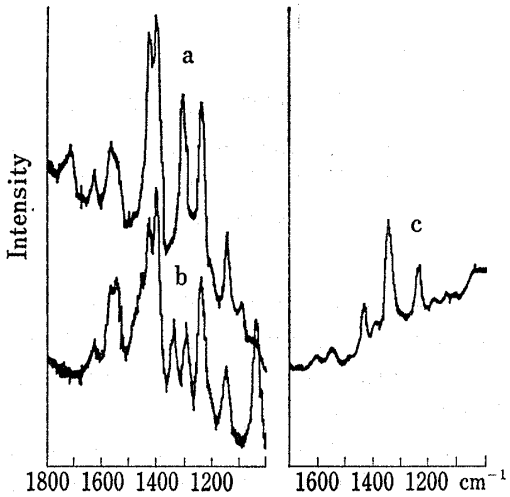


Fig. 2. Resonance Raman Spectra of 2(4BTA)4MePh

a) 1×10^{-2} M in acetone-d_6.
b) 1×10^{-3} M in CH_3OD.
c) 3.3×10^{-3} M in a 2:1 mixture of aceone-d_6 and 0.1 N KOH.

5) W.J. Geary, G. Nickless and F.H. Pollard, *Anal. Chim. Acta*, **27**, 71 (1962).
6) K. Machida, Bak Kwang Kim, Y. Saito and T. Uno, *Bull. Chem. Soc. Jap.*, **47**, 78 (1974).

II shows the frequency of the strongest resonance Raman band observed in the region between 1500 and 1000 cm^{-1}. In the undissociated form, the benzothiazolylazophenols show the Raman band assignable to the N=N streching vibration near 1400 cm^{-1} as seen at the typical example illustrated in Fig. 2. In the benzothiazolylazonaphthols, on the other hand, 2-substituted benzothiazolylazo compounds show the Raman band at 1375 cm^{-1} assignable to the N=N streching vibration, but 4-substituted benzothiazolylazo compound does not show the strongest Raman band near 1400 cm^{-1} and shows very strong Raman bands near 1500 and 1225 cm^{-1}, which may be assigned to the naphthalene ring and N–N streching vibrations, respectively, attributed to the hydrazone form (Fig. 3a). On the contrary, in the dissociated form, the benzothiazolylazophenols exhibit the typical Raman spectra of azo form, but the frequencies of their N=N streching vibrations are low compared with that in the undissociated form (Fig. 2). This suggests that the azo form is predominant over the hydrazone form in this resonance, but the contribution of the hydrazone form is not entirely neglected. In contrast, the hydrazone form may be much predominant over the azo form in the benzothiazolylazonaphthols (Fig. 3b).

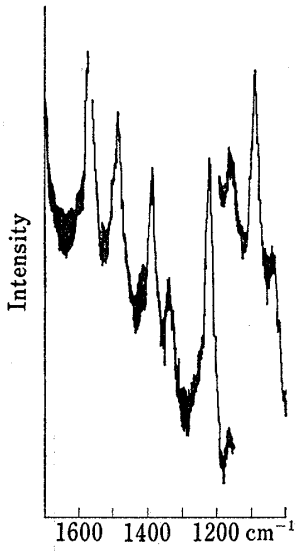


Fig. 3a. Resonance Raman Spectrum of 1(4BTA)2NT in Acetone-d_6
Conc.: 1×10^{-3} M.

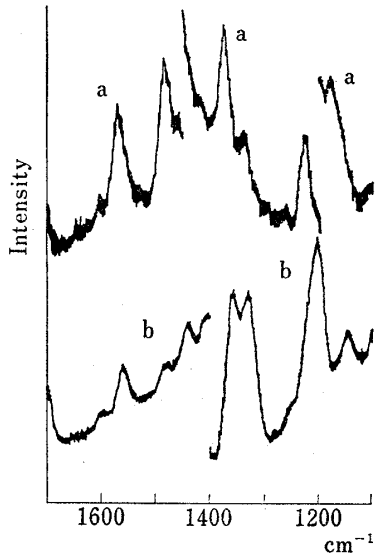


Fig. 3b. Resonance Raman Spectra of 1(4BTA)2NT
a) 2×10^{-4} M in CH_3OD.
b) 1×10^{-3} M in a 9:1 mixture of acetone-d_6 and 0.1 N KOH.

The change in the electronic structures of the benzothiazolylazo derivatives on the reaction with metal ions is an interesting subject. In Fig. 4a and 4b the Raman spectra of the metal chelates of 2(4BAT)4MePh are shown as examples. In any ligand, investigated, the Raman spectrum changes remarkably on chelating with metal ions. In the spectra of the metal chelates, the strongest resonance Raman band observed between 1335 and 1355 cm^{-1} may be assigned to the N=N streching vibration, and therefore it can be concluded that the azo form is predominant in the chelating form. However, their frequencies are low and this may be due to the decrease of the bond order of the azo group resulted by the coordination to metal ions; this may be attributed to that the azo group decreases its double bond character, resulting the formation of a condensed and resonanced ring structure by the coordination to metal ions. The Raman spectrum of the metal chelate of any benzothiazolylazo derivatives is independent on the metal ion. In view of this fact, the ligands seem to coordinate to metal ions in the same manner. It was clarified potentiometrically[1] and spectrophotometrically that the copper chelate is constituted of both 1:1 and 2:1 in the molar ratio of ligand-to-metal.

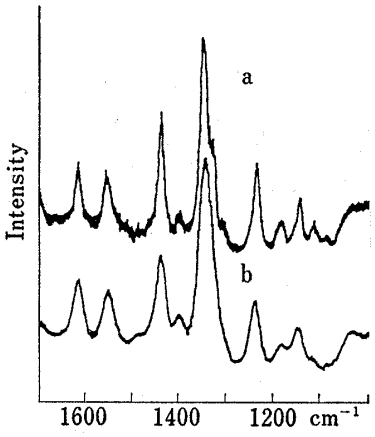


Fig. 4a. Resonance Raman Spectra of Metal Chelates of 2(4BTA)4MePh
a) nickel chelate in a 5:1 mixture of acetone-d_6 and water (ligand: Ni^{2+}=1:1).
b) zinc chelate in a 2:1 mixture of acetone-d_6 and water (ligand: Zn^{2+}=1:1); conc., 2.5×10^{-3} M.

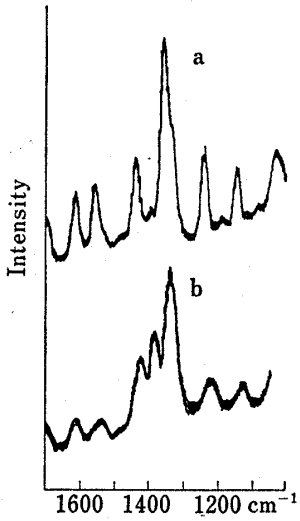


Fig. 4b. Resonace Raman Spectra of Copper Chelate of 2(4BTA)4MePh
a) 1.6×10^{-3} M in a 2:1 mixture of acetone-d_6 and water (ligand: Cu^{2+}=1:1).
b) 1.6×10^{-3} M in a 2:1 mixture of acetone-d_6 and water (ligand: Cu^{2+}=2:1), KOH alkaline.

As shown in Fig. 4b, the slight shift in the frequency of the N=N stretching vibration was only observed between the Raman spectra of 1:1 and 2:1 copper chelates. It may be accounted for this fact that in both 1:1 and 2:1 chelates the ligand coordinates to Cu^{2+} in the same manner. Accordingly, the copper chelate probably has a plane structure in the molar ratio of 1:1 ligand-to-metal and octahedron structure in 2:1, similarly to the nickel and the cadmium chelates. The slight shift in the frequency of the N=N stretching vibration may be due to the difference in steric structures.

The structures of the benzothiazole derivatives and their metal chelates in the solid state are discussed next. Figure 5 shows the IR spectra of NS4ABT and its deuterated compound. The IR spectrum of its zinc chelate is illustrated in Fig. 6. In the spectrum of NS4ABT, the band of the OH stretching vibration is broad and undetectable because of a strong intramolecular hydrogen bond. By elemental analysis and chelatometric titration, it was clarified

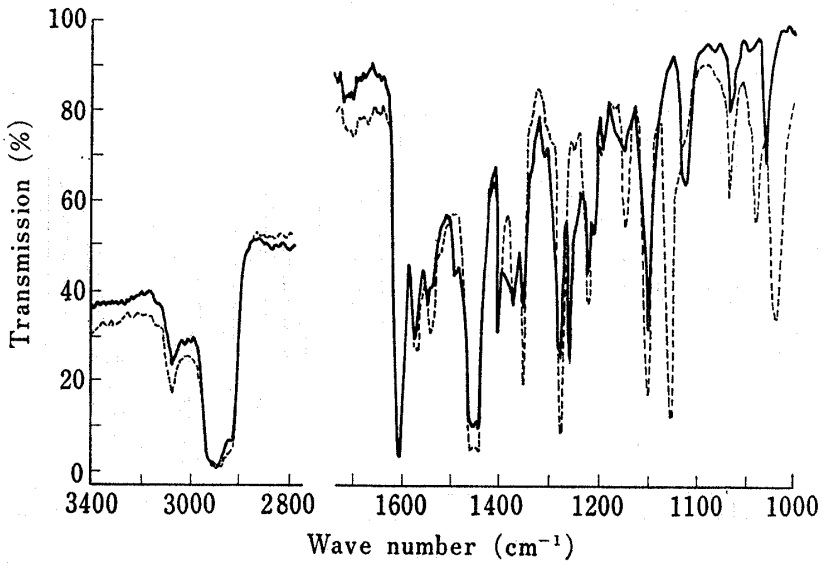


Fig. 5. Infrared Spectra of NS4ABT (Solid Line) and Its Deuterated Compound (Dotted Line) dispersed on Nujol mull

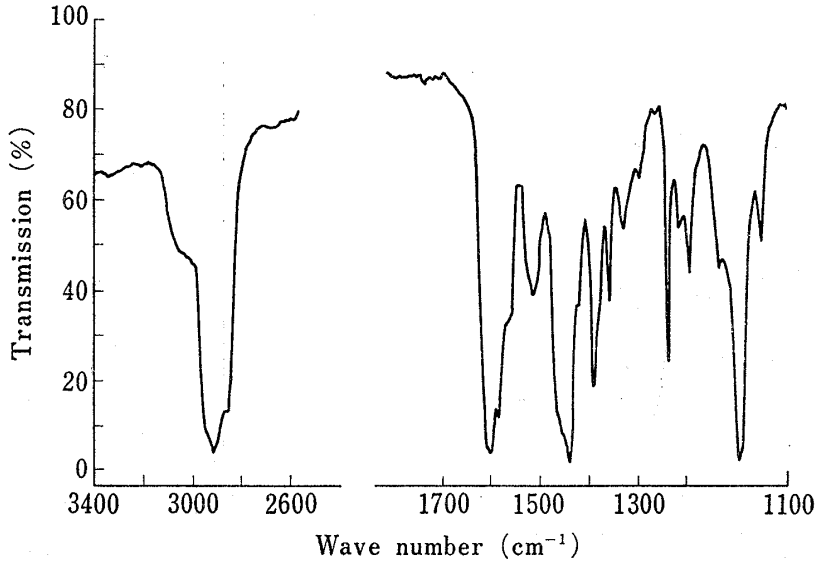


Fig. 6. Infrared Spectrum of Zinc Chelate of NS4ABT dispersed on Nujol mull

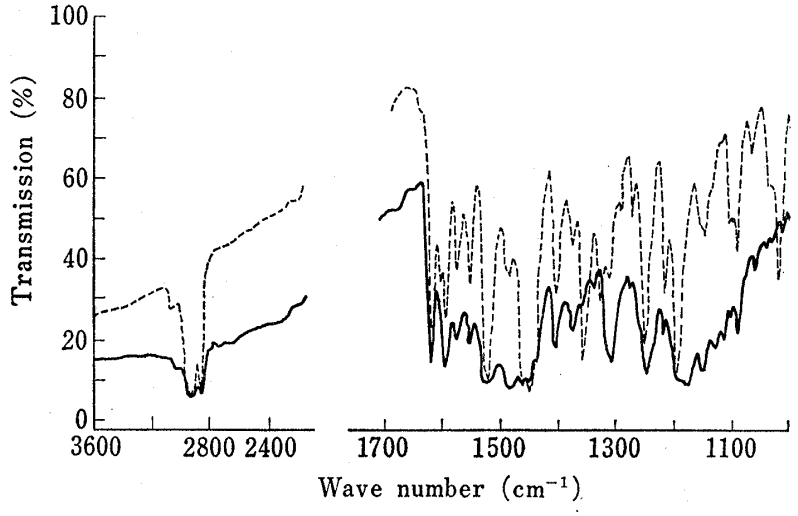


Fig. 7. Infrared Spectra of 1(2BTA)2NT (Solid Line) and Its Deuterated Compound (Dotted Line) dispersed on Nujol mull

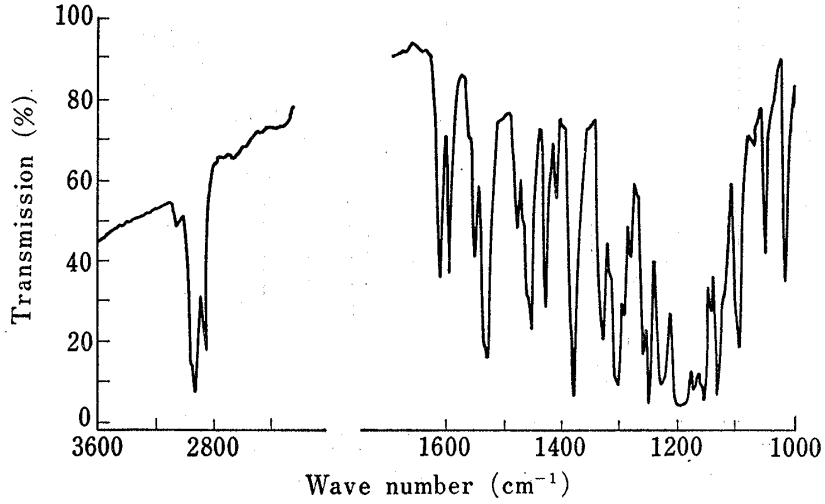


Fig. 8. Infrared Spectrum of Nickel Chelate of 1(2BTA)2NT dispersed on Nujol mull

that the composition of the zinc chelate is $Zn(NS4ABT)_2$. The bands at 1613 and 1552 cm^{-1} assigned to C=N stretching vibrations of the azomethine group and the thiazole ring in NS4-ABT shift to 1605 and 1518 cm^{-1} in its zinc chelate, respectively. These facts suggest the coordination of NS4ABT to zinc through the nitrogen atoms of the azomethine group and the thiazole ring. In addition, the 1495 cm^{-1} OH bending and the 1268 cm^{-1} C–O stretching in NS4ABT are both absent in the spectrum of the complex, and this may be due to the contribution of OH group in binding with zinc. In view of these facts, NS4ABT may act as a terdentate ligand with zinc and the resulting zinc chelate may have an octahedron structure. In this structure the ligand may have a plane structure, which may be favorable for fluorescence. In fact, this zinc chelate emits a strong fluorescence both in the solid state and in solutions.[7]

Figure 7 shows the IR spectra of 1(2BTA)2NT and its deuterated compound. Figure 8 shows the IR spectrum of its nickel chelate. Morgan measured the IR spectra of the azo compounds derived from β-naphthol in the solid and in solutions, and assigned the band at 1620 cm^{-1} to C=O stretching vibration attributed to the hydrazone form.[8] As shown in Fig. 7, the spectrum of 1(2BTA)2NT has the band at 1620 cm^{-1}. And the band is not influenced by the deuteration. This band shifts to 1608 cm^{-1} in the nickel chelate. Ordinarily, the C–H stretching vibration of naphthalene skeleton is also observed in this region, but this band may be assigned to C=O stretching vibration in view of the shift in the nickel chelate. This fact suggests that 1(2BTA)2NT has a hydrazone structure. However, the bands at 1440, 1490, and 1310 cm^{-1} may be assigned to N=N streching, OH bending and C–O stretching vibrations, respectively, and these bands shift to lower frequencies in the nickel chelate. This fact suggests that 1(2BAT)2NT has an azo structure. Based on X-ray evidence, Kurahashi showed that the azo and hydrazone tautomers co-exist in the crystalline state in 1-(2-thiazolylazo)-2-naphthol.[9] The IR spectra in Fig. 7 and 8 may suggest that the azo and hydrazone tautomers also co-exist in the solid state of 1(2BTA)2NT. The band at 1576 cm^{-1} assigned to the C=N stretching vibration of the thiazole ring also shifts to 1558 cm^{-1} in the nickel chelate and this suggests the coordination of 1(2BTA)2NT to nickel through the nitrogen atom of the thiazole ring. It was found by elemental analysis that the composition of the nickel chelate of 1(2BTA)2NT is $Ni[1(2BTA)2NT]_2$. Therefore, $Ni[1(2BTA)2NT]_2$ may have an octahedron structure.

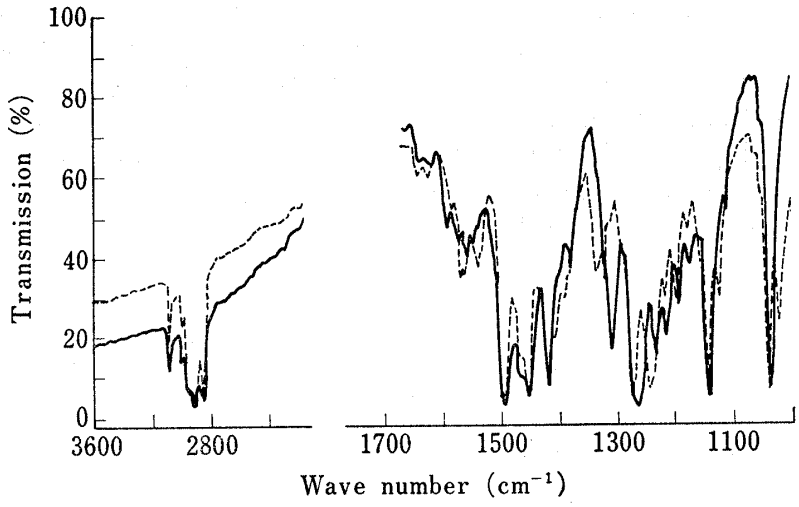


Fig. 9. Infrared Spectra of 2(4BTA)4MePh (Solid Line) and Its Deuterated Compound (Dotted Line) dispersed on Nujol mull

7) N. Shimidzu and T. Uno, *Chem. Pharm. Bull.* (Tokyo), **21**, 762 (1973).
8) K.J. Morgan, *J. Chem. Soc.*, **1961**, 2151.
9) M. Kurahashi, *Chem. Lett.*, **1974** (2), 181.

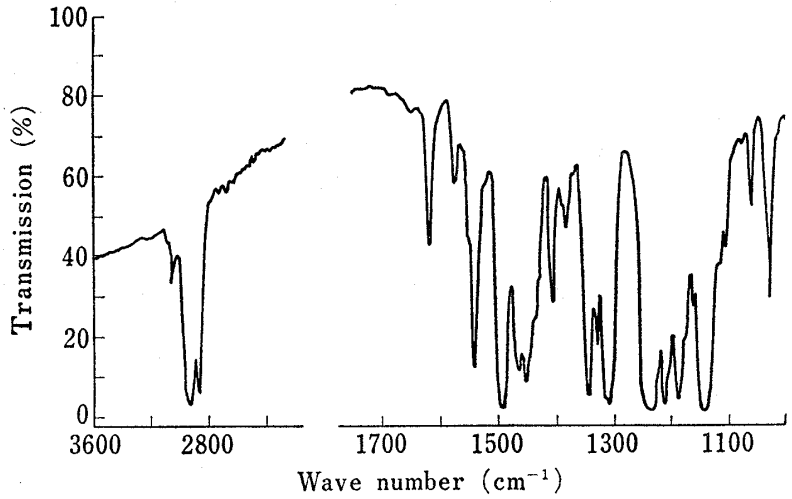


Fig. 10. Infrared Spectrum of Nickel Chelate of 2(4BTA)4MePh dispersed on Nujol mull

Figure 9 shows the IR spectra of 2(4BTA)4MePh and its deuterated compound. Figure 10 shows the IR spectrum of its nickel chelate. In the spectrum of 2(4BTA)4MePh, no band was observed near 1620 cm^{-1} differing from that of 1(2BTA)2NT and hence it is suggested that 2(4BTA)4MePh has an azo structure. The bands at 1560, 1419 and 1310 cm^{-1} in 2(4BTA)-4MePh may be assigned to the C=N stretching vibration of thiazole ring, the N=N stretching vibration and the OH bending, respectively and they are not observed in the spectrum of its nickel chelate. However, the band at 1617 cm^{-1}, which may be assigned to C=O stretching vibration, is observed in the spectrum of the nickel chelate and consequently the hydrazone form may be predominant in the nickel chelate. It was clarified by elemental analysis that the composition of the nickel chelate is $Ni[2(4BTA)4MePh]_2$.

The magnetic susceptibilities, $\mu_{eff.}$, of $Ni[1(2BTA)2NT]_2$ and $Ni[2(4BTA)4MePh]_2$ are 3.01 and 3.07 B.M., respectively, and therefore, the number of the unpaired electrons in these nickel chelates is 2. Nickel is d^8 and both the octahedral outersphere (sp^3d^2) and the tetrahedral (sp^3) complexes have two unpaired electrons, which give the value of 2.83 B.M. by the estimation from the number of the spin. However, the magnetic moment obtained by experiments, ordinarily, differs to some extent from the above theoretical value. With the nickel complexes in the solid, the experimental values have been generally observed between 2.9 and 3.3 B.M. in octahedral, and between 3.2 and 4.0 B.M. in tetrahedral.[10] Therefore, $Ni[1(2BTA)2NT]_2$ and $Ni[2(4BTA)4MePh]_2$ may have octahedral outer-sphere structures.

The manner in the coordination of the benzothiazole derivatives to metal ions in the solid is in agreement with those in solutions.

10) A. Earnshaw, "Introduction to Magnetochemistry," Academic Press Inc., Ltd., London.