# การสังเคราะห์เอโซเบนซีนที่มีหมู่ยูเรียเพื่อเป็นตัวรับและเซนเซอร์สำหรับไดคาร์บอกซิเลตแอนไอออน

นางสาววันวิสา เจนรุ่งโรจน์สกุล

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# SYNTHESIS OF AZOBENZENE CONTAINING UREA GROUPS AS DICARBOXYLATE ANION RECEPTOR AND SENSOR

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**A Thesis Submitted in Partial Fulfillment of the Requirements**
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วันวิสา เจนรุ่งโรจน์สกุล : การสังเคราะห์เอโซเบนซีนที่มีหมู่ยูเรียเพื่อเป็นตัวรับและเซนเซอร์สำหรับไดคาร์บอกซิเลตแอนไอออน (SYNTHESIS OF AZOBENZENE CONTAINING UREA GROUPS AS DICARBOXYLATE ANION RECEPTOR AND SENSOR) อาจารย์ที่ปรึกษา : ผศ.ดร. ธวัชชัย ตันทุลานิ; 131 หน้า. ISBN 974-17-3697-5

ได้ทำการสังเคราะห์อนุพันธ์ของเอโซเบนซีนที่มีหมู่ยูเรียและไธโอยูเรียทั้งหมด 8 ชนิด โดยปฏิกิริยาระหว่างไดอะมิโนเอโซเบนซีนกับไอโซไซยาเนตหรือไอโซไธโอไซยาเนต จากนั้นทำการศึกษาสมบัติการเกิดสารประกอบเชิงซ้อนของลิแกนด์ 2b และ 5a กับไดคาร์บอกซิเลตชนิดต่างๆ เช่น ออกซาเลต มาโลเนต ซัคซิเนต กลูทาเลต อะดิเปต พิมิเลต ซับเบอเรต และ อะซิเลต กระทำโดยการไทเทรตด้วยเทคนิคโปรตรอนนิวเคลียร์แมกนีติกเรโซแนนซ์ (เอ็นเอ็มอาร์) พบว่าลิแกนด์ 2b และ 5a สามารถเกิดสารประกอบเชิงซ้อนในอัตราส่วน 1:1 กับไดคาร์บอกซิเลต โดยลิแกนด์ 2b และ 5a มีค่าคงที่ของการรวมตัวกับซับเบอเรตมากที่สุด และจากการศึกษาสมบัติการเกิดสารประกอบเชิงซ้อนของลิแกนด์ 2d และ 5d กับไดคาร์บอกซิเลตแอนไอออนด้วยเทคนิคยูวี-วิสสิเบิลสเปกโตรโฟโตเมทรีพบว่า ลิแกนด์ 2d และ 5d เกิดการเปลี่ยนแปลงของสเปกตรัมอย่างชัดเจน และยังสามารถเห็นการเปลี่ยนแปลงของสีของสารละลาย 2d และ 5d ได้ด้วยตาเปล่าเมื่อจับกับไดคาร์บอกซิเลตแอนไอออน นอกจากนี้ยังศึกษาทรานส์-ซิสไอโซเมอไรเซชันของลิแกนด์ทั้ง 4 ชนิดโดยการฉายแสงยูวี ลิแกนด์ 2b และ 5a หลังการฉายแสงยูวีแล้วศึกษาการเกิดสารประกอบเชิงซ้อนกับไดคาร์บอกซิเลตแอนไอออนด้วยเทคนิคเอ็นเอ็มอาร์ไทเทรชัน พบว่าลิแกนด์ 2b และ 5a ในรูป ซิสมีค่าคงที่ของการรวมตัวกับซับเบอเรตมากกว่าก่อนฉายแสง 10-30 เท่า ซึ่งแสดงว่าลิแกนด์ 2b และ 5a ในรูปซิสไอโซเมอร์มีขนาดของโพรงที่พอเหมาะกับความยาวของซับเบอเรตมากที่สุด สำหรับลิแกนด์ 2d และ 5d เมื่อทำการฉายแสงยูวีพบว่า ลิแกนด์ 2d และ 5d เกิดทรานส์-ซิสไอโซเมอไรเซชันได้ เมื่อติดตามการเปลี่ยนแปลงด้วยเทคนิคยูวี-วิสสิเบิลสเปกโตรโฟโตเมทรี และยังสามารถเห็นการเปลี่ยนแปลงได้ด้วยตาเปล่าเมื่อเติมไดคาร์บอกซิเลตแอนไอออน



ภาควิชา เคมี ลายมือชื่อนิสิต.....

สาขาวิชา เคมี ลายมือชื่ออาจารย์ที่ปรึกษา.....

ปีการศึกษา 2546

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WANWISA JANRUNGROATSAKUL: SYNTHESIS OF AZOBENZENE CONTAINING UREA GROUPS AS DICARBOXYLATE ANION RECEPTOR AND SENSOR. THESIS ADVISOR: ASSIST. PROF. THAWATCHAI TUNTULANI, Ph.D. 131 pp. ISBN 974-17-3697-5.

Eight azobenzene derivatives containing urea and thiourea units were synthesized by coupling diaminoazobenzenes with isocyanate or thioisocyanate. Complexation studies of ligands **2b** and **5a** with dicarboxylate anions such as oxalate, malonate, succinate, glutarate, adipate, pimelate, suberate and azelate were carried out by $^{1}$H-NMR titrations. Ligands **2b** and **5a** were able to form 1:1 complexes with all dicarboxylate anions. Ligands **2b** and **5a** form the most stable complexes with suberate anion. Complexation studies of ligands **2d** and **5d** with dicarboxylate anions by UV-visible spectrophotometry show dramatic change in UV spectra. Additionally, ligands **2d** and **5d** can bind dicarboxylate anions and give a color change that can be detected by naked eyes. Ligands **2b, 2d, 5a** and **5d** underwent an observable *cis-trans* isomerization by irradiation with the UV light. Complexation studies of **2b** and **5a** with anions after irradiation were carried out by $^{1}$H-NMR titrations. Association constants of ligands **2b** and **5a** (the *cis* form) toward suberate were about 10-30 times higher than ligands **2b** and **5a** before irradiation (the *trans* form). It was attributed to the matching of the chain length of dicarboxylate with the cavity size of the *cis*-form of ligands **2b** and **5a**. After irradiation, ligands **2d** and **5d** in DMSO solution underwent *trans* to *cis* isomerization and gave a color change that was able to be detected by naked eyes upon addition of dicarboxylate anions.

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## List of Abbreviation and Signs

| | |
|---|---|
| Å | Angstrom |
| °C | Degree Celcius |
| δ | Chemical shift |
| equiv. | Equivalent |
| g | Gram |
| $^1$H-NMR | Proton Nuclear Magnetic Resonance |
| Hz | Hertz |
| *J* | Coupling constants |
| $K_a$ | Association constant |
| M | Molar |
| mL | Milliliter |
| mmol | Millimole |
| RT | Room Temperature |
| s, d, t, m | Splitting patterns of $^1$H-NMR (singlet, doublet, triplet and multiplet) |

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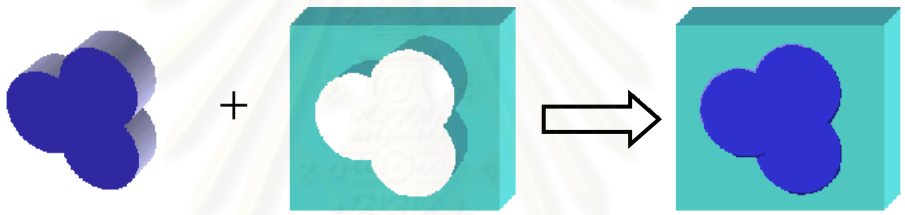
# CHAPTER I

# INTRODUCTION

## 1.1 Molecular Recognition

Supramolecular chemistry[1-2] base on molecular recognition has added a new dimension to chemistry. Given any substrates (neutral molecules, cations or anions), an appropriate receptor, possessing structural features suitable for substrate recognition, can be designed. This concept is illustrated in Figure 1.1.



substrate receptor

**Figure 1.1** The basic principle of molecular recognition.

Synthetic receptors have been the challenge of designing and building molecules having shapes and dimensions suitable for hosting any kind of substrates and ability of establishing with substrate interactions of a sufficient energy (e.g. hydrogen bonds, electrostatic interactions, π-interactions etc.). Binding interactions have found applications in myriad chemical and biochemical processes.[3-4]

## 1.2 Anion Receptors

The development of receptors for biologically important anions is emerging as a research area of great importance within the field of supramolecular chemistry. The design of anion receptors is particularly challenging because anionic species have a wide variety of geometries[5] (such as spherical, linear, trigonal planar, tetrahedral and

octahedral). Difference in geometry between anions is an important factor to account for in the design of selective anion receptors, although it is not to synthesize receptor molecules with complementary binding sites in a proper three-dimensional arrangement.

Anion receptors can be mainly divided into two classes: positively charged[6-7] and neutral anion receptors.[8-10] Positively charged anion receptors use ammonium derivatives or guanidinium centers for binding negatively charged anions. Neutral anion receptors employed hydrogen bonding NH-based donors such as pyrroles, amides and urea/thiourea or Lewis acids for binding anions.[11]

Urea and thiourea are particularly good hydrogen bond donors and are excellent receptors for anions such as carboxylate and dihydrogenphosphate *via* the formation of two hydrogen bonds.[12]

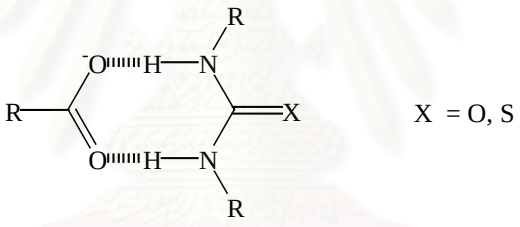
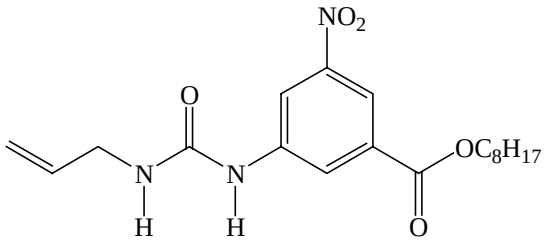



**Figure 1.2** The ideal two-point interaction between (thio)urea and carboxylate anions.

Because hydrogen bonding is directional in character and correct orientation of the hydrogen bond donors can provide selective anion recognition. Wilcox and co-workers[13] were the first to utilise urea and thiourea for carboxylate binding and reported that urea **1** bind, for example, tetrabutylammonium (TBA) benzoate in $CDCl_3$ ($K_a$ = 2.7 x $10^4$ $M^{-1}$). Large downfield shifts of the signals for the NH protons were observed in $^1$H-NMR titration experiments, indicating strong hydrogen between urea hydrogens and carboxylate oxygens.



**1**

**Figure 1.3** Structure of compound **1**.

Reinhoudt and co-workers[14] produced a series of acyclic tripodal receptors containing amide groups **(2-3)**. Receptor **2** bind $H_2PO_4^-$ with an association constant of 6.1 x $10^3$ $M^{-1}$ in acetronitile. The increase electrophillicity of sulfonamide NH moieties in receptor **3**, in combination with preorganization of the binding site by π-stacking, enhances the $H_2PO_4^-$ binding with receptor **3** ($k_a$ = 1.4 x $10^4$ $M^{-1}$).

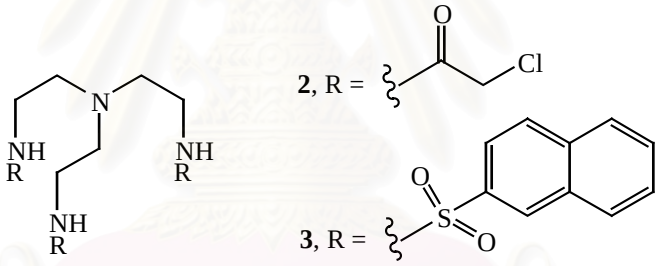
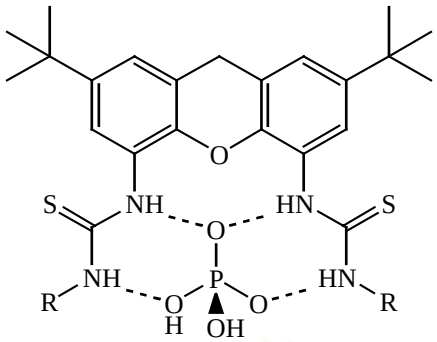


**Figure 1.4** Structure of compounds **2** and **3**.

Recently Umezawa and co-workers[15] have produced a series of acyclic thiourea cleft molecules including some highly preorganized systems containing a xanthene spacer. Receptors **4** and **5** were obtained from coupling 2,7-di-*tert*-butyl-9,9-dimethyl-4,5-xanthenediamine with thioisocyanates. Association constants were measured by $^1$H-NMR titration with DMSO-$d_6$ as solvent (see Table 1.1). A Job's plot showed a 1:1 complex stiochiometry and titrations gave association constant up to 5.5 x $10^4$ $M^{-1}$ for receptor **4** with $H_2PO_4^-$ ion and 1.95 x $10^5$ $M^{-1}$ for receptor **5**. The phenyl substituent leads to much stronger complex stabilities because electron withdrawing effect of phenyl groups increases the acidity of the thiourea. The selectivity for $H_2PO_4^-$ ion can be attributed to the complementary hydrogen bonding array present in these clefts that can form four hydrogen bonds to each $H_2PO_4^-$.



**4**, R = Bu

**5**, R = Ph

**Figure 1.5** Receptors **4** and **5** can coordinate dihydrogen phosphate anions via four hydrogen bonds.

**Table 1.1** Stability constant ($M^{-1}$)[a] from $^1$H-NMR titration experiments in DMSO-$d_6$.

| Anion[a] | Host | |
|---|---|---|
| | **4** | **5** |
| $H_2PO_4^-$ | 55000 | 195000 |
| $CH_3COO^-$ | 38000 | [b] |
| $Cl^-$ | 840 | 1000 |

[a] Added as tetrabutylammonium salts

[b] Not determined

### 1.3 Anion sensor

The field of molecular recognition association with signaling of reversible anion binding using synthetic sensors has witnessed increasing popularity in recent years.[16] Such systems generally contain some combination of substrate recognition functionality (receptor) and signaling unit, ether directly linked[17-19] or appropriately associated in a noncovalent manner.[20-21] The most common modes of signal transduction typically involve electrochemical or optical changes in the sensor incurred by association of the analyte with the receptor. Figure 1.6 illustrates the mechanism of an anion sensor.

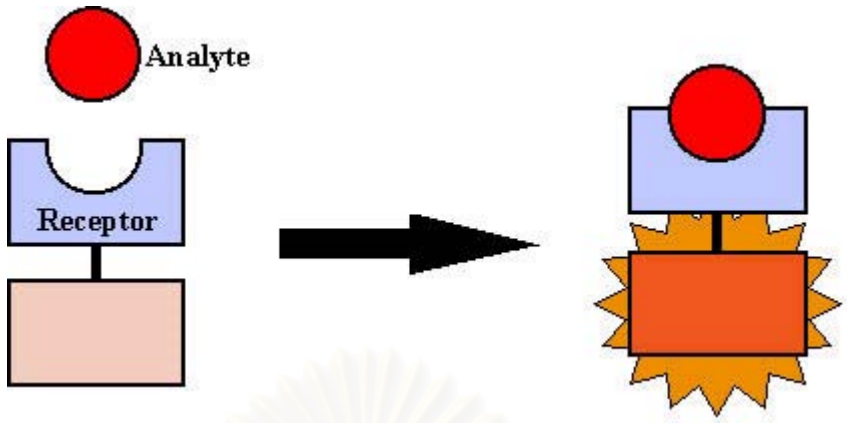


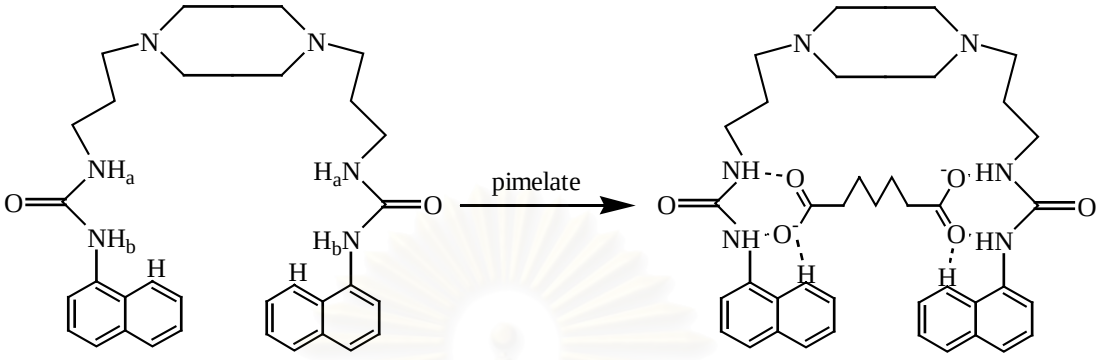

**Figure 1.6** Action of anion sensor.

Electrochemical-based sensing has proved a popular method for signaling the recognition of analytes. The majority of electrochemical-based sensors employ transition metals or lanthanides for both analyte binding and electrochemical signaling through changes in metal redox potentials upon anion-receptor complexation.[22]

Optical signaling of anion recognition typically involves quenching or enhancement of a chromophore's absorbtion[23] or a fluorophore's fluorescence emission[24-27] upon proximal association of the analyte. While the utilities of these approaches are becoming increasingly appreciate in term of both qualitative and quantitative analysis, the number of optical signaling sensors available at present for anionic substrates remains quite limited. Of particular interested in this regard are "colorimetric anion sensors" species that would allow the so-called "naked-eye" detection of anions without resort to any spectroscopy instrumentation.[16]

For example, fluorescent sensor of dicarboxylate anion has been realized by Mei and Wu.[28] The fluorescence quenching and a new emission of compound **6** (Figure1.7) through photoinduced electron transfer (PET) process by different dicarboxylate anions has been studied. Its sensitivity for recognition depends strongly on the chain length of dicarboxylate anions and the distance between urea units. $^{1}$H-NMR spectra indicate that a 1:1 complex is formed between compound **6** and dicarboxylate anions through hydrogen bonding interaction. Results also indicate that

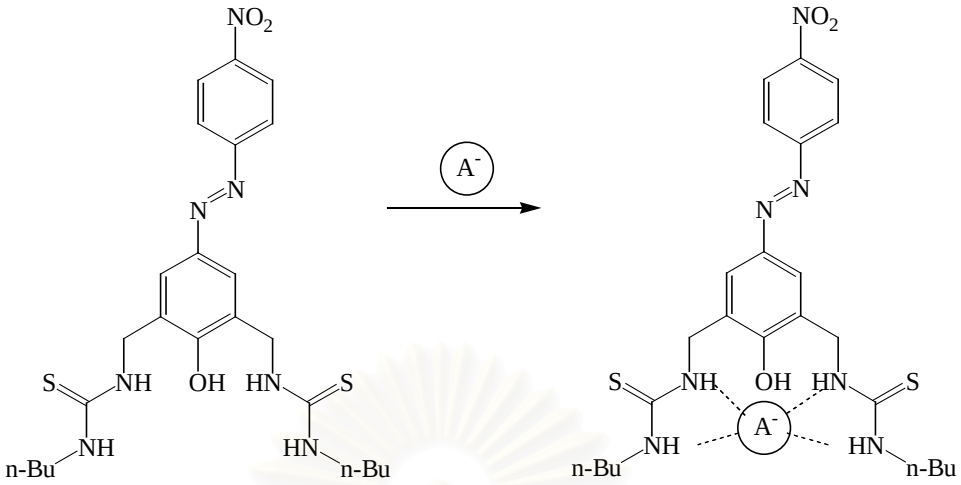
multiple hydrogen bonding interactions may effect the stability of complex and play an important role in molecular recognition.




**6** **6 - pimelate**

**Figure 1.7** Structure of compound **6** and it complexation with pimelate anion.

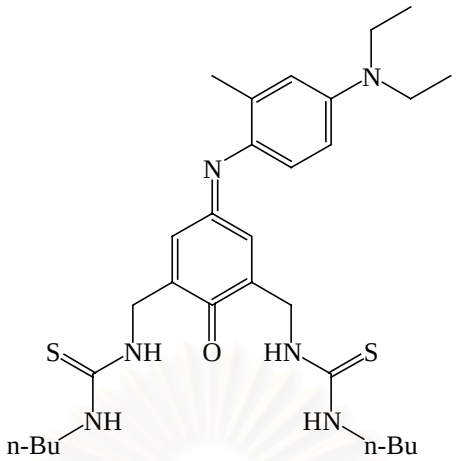
In 2001, Hong and co-workers[29] have reported anion coordination with a nitro-azophenol base sensor, compound **7**. Association constants for anion binding were determined by $^1$H-NMR and UV-vis titration in $CDCl_3$. The selectivity trends of anion-induced color change for **7** were determined to be $F^-$ ~ $H_2PO_4^-$ ~ $AcO^-$ >> $HSO_4^-$ ~ $Cl^-$ > $Br^-$ ~ $I^-$ because of the basis of anion basicity. In the absence of anions, the UV-vis absorption spectrum of **7** showed on absorption maximum peak at 376 nm. With addition of $H_2PO_4^-$, the peak at 376 nm decreased while a new peak appeared at 529 nm, concomitant with solution color change from light yellow to deep red. This may be due to the electronic excitation through charge transfer from oxygen donor of the phenol to an acceptor substituent ($-NO_2$) of the chromophore. The excited state would be more stabilized by anion binding, resulting in a bathochromic shift in the absorption maxima as well as color change. Clear isobestic points were observed, which shows the existence of two states of 1:1 complex. These results indicated that color change of **7** is suitable for the “naked-eye” monitoring of the binding of selected anions such as $H_2PO_4^-$ and $AcO^-$.




**7**

**Figure 1.8** Structure and proposed mode of anion binding for **7**.

Later, Hong and co-workers changed the signaling unit in compound **7** from nitro-azobenzene to indoaniline.[30] Compound **8**, a new chromogenic indoaniline-thiourea-based sensor, showed significant color and UV-vis spectral changes upon binding anions. Upon the addition of $H_2PO_4^-$ or $HPO_4^{2-}$, the color of the $CHCl_3$ solution is changed from blue-green to deep blue. The association constants obtained from UV-vis titrations for complex of **8** with $H_2PO_4^-$ and $HPO_4^{2-}$ in $CDCl_3$ are $1.1 \times 10^4$ $M^{-1}$ and $2.5 \times 10^4$ $M^{-1}$, respectively. However, addition of $AcO^-$ or $F^-$, more basic anion, caused a less intense color change. This sensor, thus, allows the selective colorimetric detection of tetrahedral oxoanions such as $H_2PO_4^-$ and $HPO_4^{2-}$. The same manner as in compound **7**, compound **8** possesses four NH urea moieties and would preferably bind anions with tetrahedral geometry ($H_2PO_4^-$ and $HPO_4^{2-}$).




**8**

**Figure 1.9** Structure of compound **8**.

### 1.4 Photoresponsive systems

Complexation behavior and selectivity can be reversibly controlled by external stimulation as show in Figure 1.10.[31]


**Figure 1.10** The external stimulation infuences on the host-guest complexation.

A supermolecule incorporated with a photochromic component has introduced interesting photoresponsive properties. This concept can be applied to build model systems for theoretical studies and for photochemical molecular devices.

### 1.4.1 *Cis-trans* isomerization of unsaturated compounds

Absorption of a photon by a compound containing an olefinic link often results in *cis-trans* geometrical isomerization.[32] In many simple systems the *trans* isomer absorbs light of longer wavelength more intensely than the *cis* isomer; consequently, if long wavelength light is employed a photostationary condition is reached in which the *cis* isomer predominates. The rate of conversion of *trans* to *cis* and *cis* to *trans* isomers are equal at the **photostationary state**, which depend on structures of molecules and condition.[33]

### 1.4.2 Photochemical *cis-trans* isomerization of azobenzene

Azobenzene and their derivatives are characterized by reversible transformation form the generally more stable *trans* form to the less stable *cis* form upon irradiation with UV light ($\lambda$ = 360 nm) in solution. Thermal isomerism from the photogenerated *cis* to the *trans* form is shown in Figure 1.11. The intense absorption at 320 nm due to the $\pi$-$\pi^*$ transition of the *trans* isomer decreases during such an isomerization, while the absorption maximum due to the *cis* isomer at 430 nm which is due to the n-$\pi^*$ transition increases.[34]

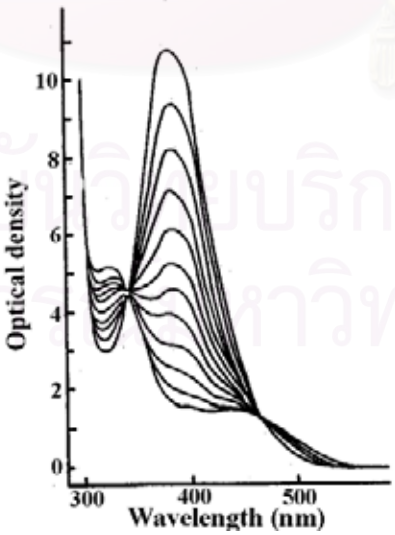


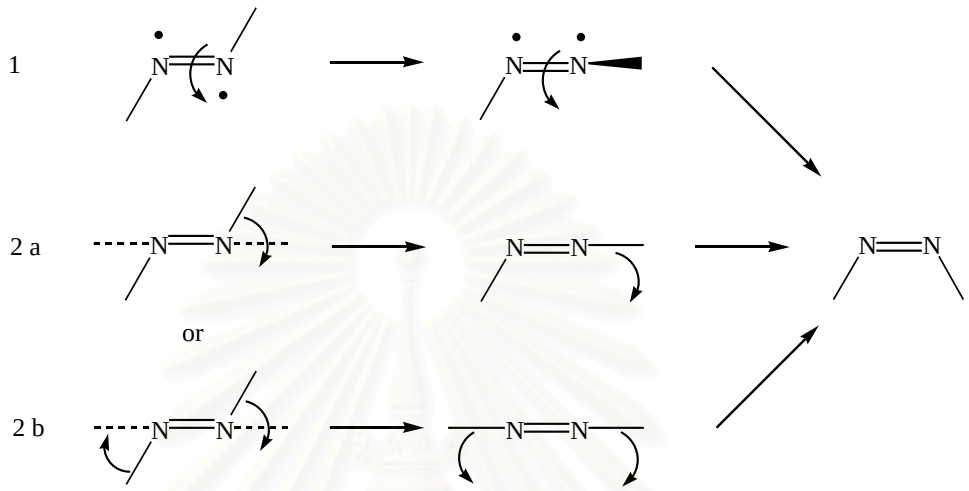

**Figure 1.11** Absorption spectra of azobenzene in $CHCl_3$ showing thermal recovery ($T$ = 28 °C).

There are two well accepted isomerization mechanisms of azobenzene :

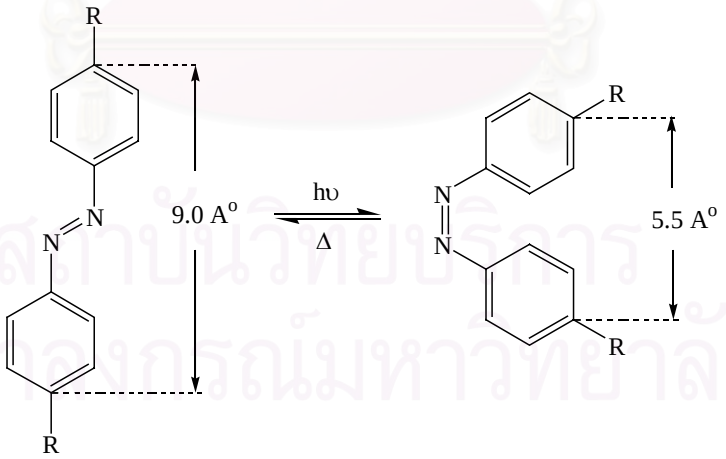
1. Twisting around the -N=N- double bond (rotation mechanism)

2 a) In-plane inversion at one of two nitrogen atoms (inversion mechanism)

b) In-plane inversion at both nitrogen atoms




The in-plane inversion mechanism is responsible for the dark isomerization, while rotation can usually occur upon light excitation.[35] However, it is not clear whether photoisomerization occurs through only rotation or along with inversion.

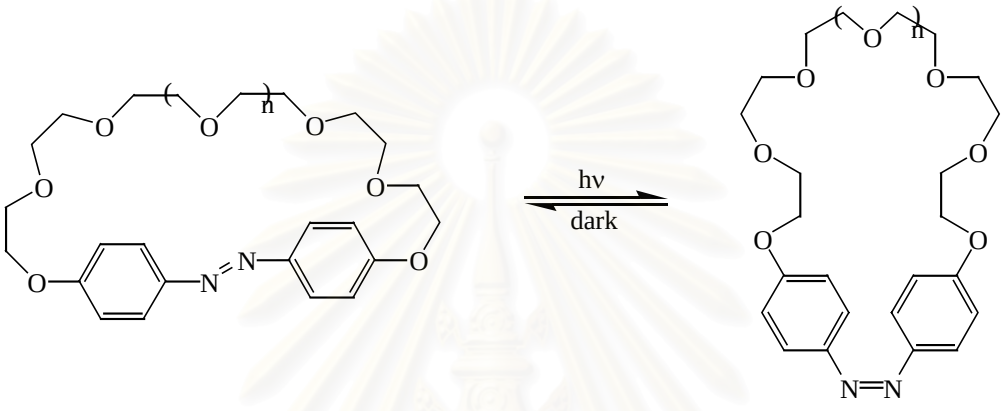



*trans-* *cis-*

**Figure 1.12** Geometrical changes of azobenzene.

Photoinduced isomerism of azobenzene also proceeds with large structural change as reflected in the dipole moment and change in geometry.[34] The

isomerization involves a decrease in the distance between the *para* carbon atoms in azobenzene about 9.0 Å in the *trans* form to 5.5 Å in the *cis* form, and the local contraction may be even greater (Figure 1.12). Likewise, *trans*-azobenzene has no dipole moment while the dipole moment of the nonplanar *cis* compound is 3.0 D. These properties are useful for probes of conformational dynamic of macromolecules by site-specific photolabeling.



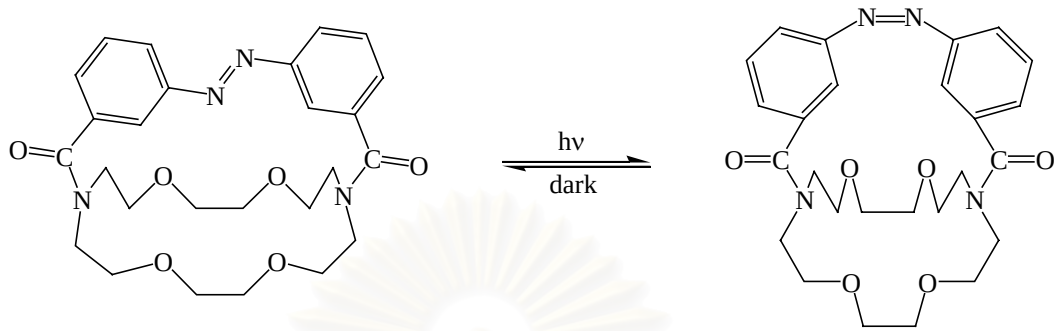

*trans*-**9** (n =1-3) *cis*-**9** (n = 1-3)

**9**

**Figure 1.13** *Trans-cis* isomerization of **9**.

For example, three new azobenzenophane-type crown ethers, (as n = 1-3), in which 4, 4/ position of azobenzene are linked by a polyoxyethylene chain (**9**)[36], were synthesized. The *trans* isomers isomerized by UV light irradiation to the *cis* isomers, and the *cis* isomers were isomerized thermally or visible light to the *trans* isomers, the interconversion being completely reversible. The solvent extraction showed that the *trans* isomers totally lack affinity toward metal ions, whereas the *cis* isomers are able to bind considerable amounts of alkali metal cations. The *cis* isomers showed spherical recognition patterns in the binding of alkali metal cations, typical of crown ethers in solution; the metal cations which provided the maximum extractability were $Na^+$ for *cis*-**9** (n = 1), $K^+$ for *cis*-**9** (n = 2) and $Rb^+$ for *cis*-**9** (n = 3). *Cis*-**9** (n = 1) cannot bind large alkali metal cations, whereas *cis*-**9** (n = 3) can bind, although not strongly, both small and large alkali metal cations. Probably, *cis*-**9** (n = 3) has a characteristic of so-called “induced fit” to small alkali metal cations. These systems

are rather interesting because an “all-or-nothing” change in the ion-binding ability takes place upon photoisomerization.

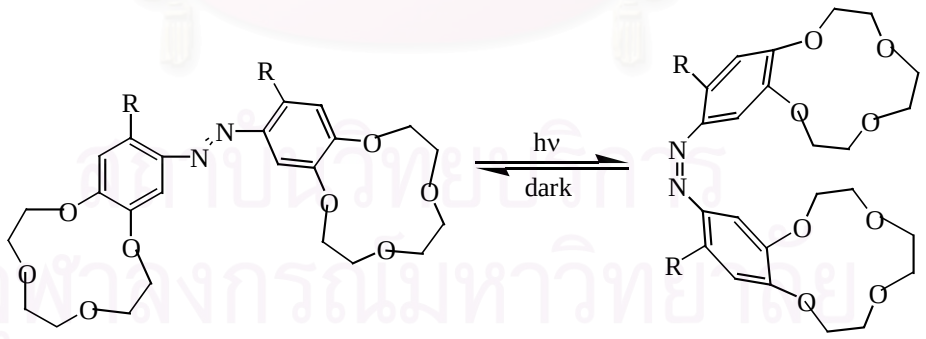



*trans*- *cis*-

**10**

**Figure 1.14** *Trans-cis* isomerization of azobenzene capped with crown ether (**10**).

The *trans*-azobenzene capped with crown ether (**10**)[37] perferably binds small metal ions such as $Li^+$ and $Na^+$. After UV-irradiation, the *trans*-azobenzene (*trans*-**10)** changes to *cis*-azobenzene (*cis*-**10**) which probably binds large metal ions such as $K^+$ and $Rb^+$. The result was rationalized in term of photoinduced expansion of crown ether size that cavity of *cis*-**10** was greater than that of *trans*-**10**.




*trans*- *cis*-

**11**

**Figure 1.15** *Trans-cis* isomerization of azobis(benzocrown ether), a butterfly-motion.

Shinkai and co-workers[38] synthesized azobis(benzocrown ether) (**11**), show in Figure 1.15, which possessed a butterfly-like motion. The *trans*-form isomerized by UV light irradiation to the *cis*-form, and the *cis*-form was isomerized thermally reversible to the *trans*-form. The binding ability of photoresponsive **11** was determined by solvent extraction of alkali metal salts. The results consistently suggest that *cis*-**11** form stable 1:2 cation/crown complexes with large alkali metal cations ($K^+$, $Rb^+$ and $Cs^+$), whereas *trans*-**11** form stable 1:1 cation/crown complexes with small metal cations ($Li^+$ and $Na^+$).

## 1.5 Biological Process of dicarboxylate anions

In a living cell, dicarboxylates are essential components of numerous metabolic processes, including for instance, the citric acid cycle[39] (known as Krebs cycle). Dicarboxylates such as succinate, fumarate, oxaloacetate, α-ketoglutarate and malate are importance intermediates for generating ATP[40] (adenosine triphosphate) in the citric acid cycle.

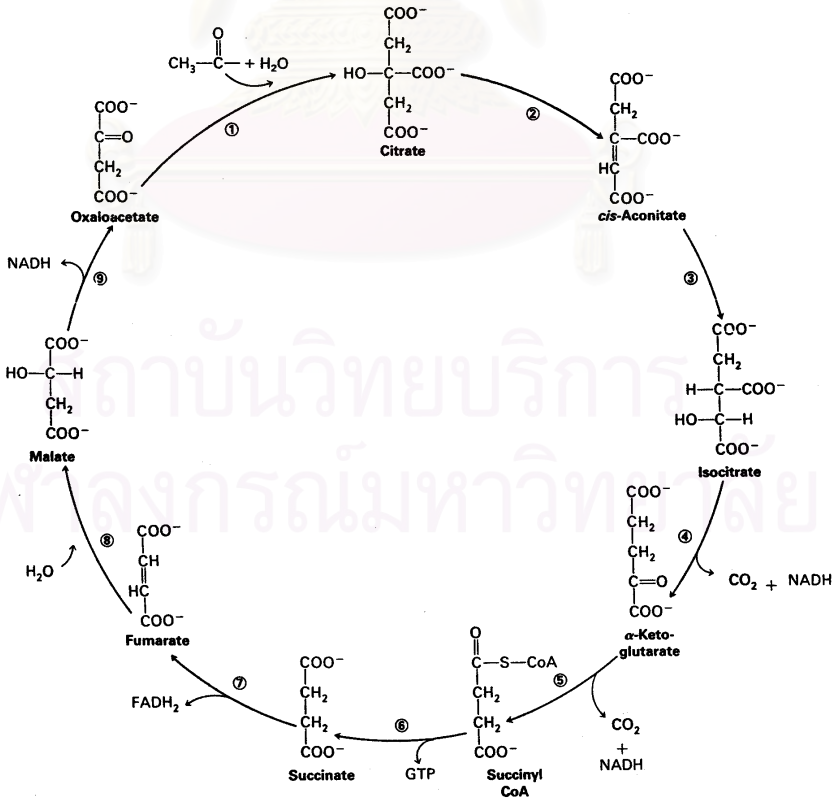
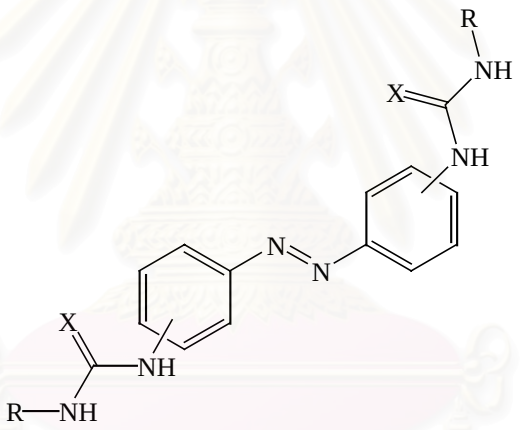



**Figure 1.16** The citric acid cycle.

## 1.6 Objectives and Scope of this research

The main goals of this research are to synthesize azobenzene containing urea or thiourea derivatives **2a-2d** and **5a-5d**. Compounds **2b**, **2d**, **5a** and **5d** employed NH-based donors urea or thiourea to serve as anion receptor. The complexation studied of compounds **2b** and **5a** with dicarboxylate anions such as acetate, oxalate, malonate, succinate, glutarate, adipate, pimelate, suberate and azelate are also studied by $^{1}$H-NMR titrations. In addition, photoisomerization using UV-irradiation of these compounds were investigated and association constants of compounds **2b** and **5a** with dicarboxylate anions were determined by $^{1}$H-NMR titrations. Complexation and photoisomerization of compounds **2d** and **5d** with dicarboxylate anions were also studies by UV-vis titrations.




**2a** ; *meta*, X = O, R = butyl

**2b** ; *meta*, X = O, R = hexyl

**2c** ; *meta*, X = O, R = phenyl

**2d** ; *meta*, X = S, R = nitrophenyl

**5a** ; *para*, X = O, R = butyl

**5b** ; *para*, X = O, R = hexyl

**5c** ; *para*, X = O, R = phenyl

**5d** ; *para*, X = S, R = nitrophenyl

**Figure 1.17** Structures of derivatives of azobenzene containing urea and thiourea (**2a-2d** and **5a-5d**).

# CHPTER II

# EXPERIMENTAL SECTION

## 2.1 General procedure

### 2.1.1 Analytical instruments

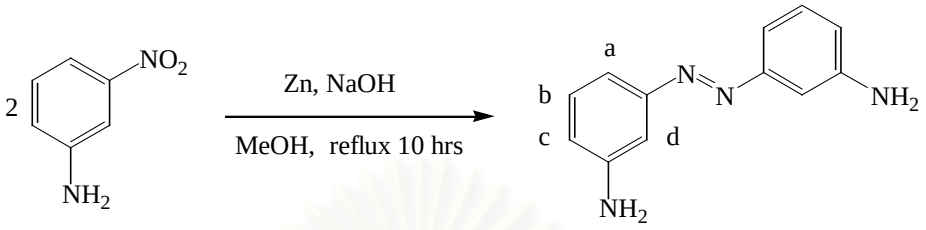
The $^{1}$H-NMR spectra were recorded on a Bruker ACF 200 MHz nuclear magnetic resonance spectrometer and a Varian 400 MHz nuclear magnetic resonance spectrometer. In all cases, samples were dissolved in deuterated chloroform, acetonitrile or dimethylsulfoxide, and chemical shifts were recorded using a residual proton signal as internal reference. Elemental analysis were analyzed on a Perkin Elmer CHON/S analyzer (PE2400 series II). UV-vis absorption spectra were acquired on a Varian Cary 50 UV-vis spectrophotometer. Infrared spectra were obtained on a Nicolet Impact 410 using KBr pellet. All melting points were taken on an Electrothermal 9100.

### 2.1.2 Materials for synthesis

All materials were standard analytical grade, purchased from Fluka, Aldrich, Carlo Erba, BHD or Merck, and used without further purification. Commercial grade solvents such as acetone, dichloromethane, methanol, hexane and ethyl acetate were distilled before used. Chromatographic separations were performed on silica gel columns (kieselgel 60, 0.063-0.200 mm, Merck). Thin layer chromatography (TLC) was carried out using silica gel plates (kieselgel 60 $F_{254}$, 1 mm, Merck). Synthesis of 3,3$^{/}$-diaminoazobenzene, **1**, and 4,4$^{/}$-diaminoazobenzene, **4**, were prepared according to the literature procedure.[41] The products were characterized by $^{1}$H-NMR spectroscopy and elemental analysis.

## 2.2 Synthesis of azobenzene derivatives

### 2.2.1 Preparation of 3,3′-diaminoazobenzene, 1




**1**

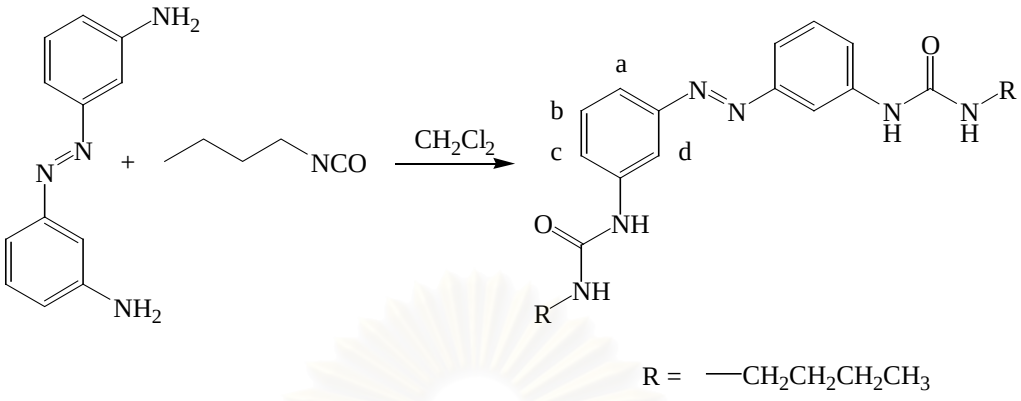
In a 250 mL two-necked round bottom flask equipped with a magnetic bar and a reflux condenser, 3-nitroaniline (5.5712 g, 40.33 mmol), zinc powder (5.8864 g, 90.56 mmol), a solution of sodium hydroxide (6.4384 g, 160.96 mmol) in 50 mL of water and methanol (100 mL) were mixed and stirred. The mixture was refluxed under nitrogen for 10 hours. The reaction mixture was filtered while hot and the precipitate of sodium zincate was washed with a small amount of methanol. The strong alkaline filtrate was not always clear: render it neutral to litmus by addition of 3 M hydrochloric acid and filtered. After that, the solvent was removed under reduced pressure on a rotary evaporator to obtain a yellowish solid. The yellowish solid was redissolved in dichloromethane and then mixed with silica gel. The product was eluted through a silica gel column with 20% ethyl acetate/dichloromethane as eluent to give a bright yellow solid (5.6183 g, 61%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 1:**

**$^1$H-NMR spectrum ($CDCl_3$):** δ (ppm) = 7.53 (dd, 2H, *J* = 7.09 Hz, -N=NAr-$H_a$$NH_2$), 7.47 (t , 2H, *J* = 2.20 Hz, -N=NAr-$H_d$$NH_2$), 7.26 (t, 2H, *J* = 8.06 Hz, -N=NAr-$H_b$$NH_2$), 6.93 (dd, 2H, J = 7.97 Hz, -N=NAr-$H_c$$NH_2$); 3.96 (s, broad, 4H, -ArN$H_2$)

**Melting point:** 111-114 °C

### 2.2.2 Preparation of 3,3′-bis(*N*′-butylureido)azobenzene, 2a




**1** **2a**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, *n*-butyl isocyanate (0.22 mL, 2.49 mmol) was added to a solution of 3,3′-diaminoazobenzene, **1**, (0.2130 g, 1.00 mmol) in dichloromethane (10 mL). The solution was stirred overnight at room temperature under nitrogen. The yellow product precipitated. The precipitate was collected by filtration and washed with dichloromethane. Recrystallization from hexane/dichloromethane/dimethylsulfoxide gave the product as pale orange solid (0.3152 g, 77%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 2a:**

**$^1$H-NMR spectrum (DMSO-*d*$_6$):** δ (ppm) = 8.86 (s, 2H, -N=NArN*H*CONH-), 8.03 (s, 2H, -N=N*Ar*-*H*$_d$NH-), 7.43 (s, 6H, -N=N*Ar*-*H*$_a$*H*$_b$*H*$_c$NH-), 6.17 (t, 2H, *J* = 5.54 Hz, -N=NArNHCON*H*-), 3.09 (q, 4H, *J* = 5.92 Hz, -NHC*H*$_2$(CH$_2$)$_2$CH$_3$), 1.43-1.22 (m, 8H, -NHCH$_2$(C*H*$_2$)$_2$CH$_3$), 0.89 (t, 6H, *J* = 7.10 Hz, -NHCH$_2$(CH$_2$)$_2$C*H*$_3$)

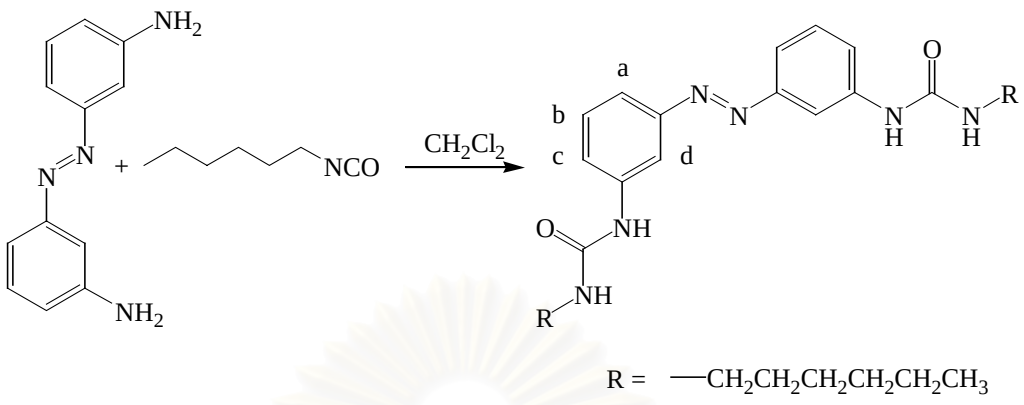
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{22}H_{30}O_6N_2$ | C, 64.37; H, 7.37; N, 20.47 |
| Found | C, 64.34; H, 7.34; N, 20.47 |

**IR spectrum (KBr (cm$^{-1}$)):** 1635 (C=O)

**Melting point:** decompose > 300 °C

### 2.2.3 Preparation of 3,3′-bis(*N*′-hexylureido)azobenzene, 2b




**1** **2b**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, hexylisocyanate (0.70 mL, 4.80 mmol) was added to a stirred solution of 3,3′-diaminoazobenzene, **1**, (0.4258 g, 2.01 mmol) in dichloromethane (20 mL) and stirring was continued overnight at room temperature under $N_2$. The precipitate that formed was filtered and washed with a small amount of dichloromethane. It was recrystallized twice from dichloromethane/hexane to give the product as white crystals (0.8640 g, 92%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 2b:**

**$^1$H-NMR spectrum ($CD_3CN$):** δ (ppm) = 8.45 (t, 2H, *J* = 2.20 Hz, -N=N*Ar*-*H*$_d$NH-), 7.75 (dd, 2H, *J* = 8.04 Hz, -N=N*Ar*-*H*$_c$NH-), 7.60 (dd, 2H, *J* = 8.23 Hz, -N=N*Ar*-*H*$_a$NH-), 7.53 (s, broad, 2H, -N=NArN*H*CONH-), 7.42 (t, 2H, *J* = 8.16 Hz, -N=N*Ar*-*H*$_b$NH-), 5.43 (s, broad, 2H, -N=NArNHCON*H*-), 3.15 (q, 4H, *J* = 5.97 Hz, -NHC*H*$_2$(CH$_2$)$_4$CH$_3$), 1.51-1.28 (m, 16H, -NHCH$_2$(C*H*$_2$)$_4$CH$_3$), 0.88 (t, 6H, *J* = 6.54 Hz, -NH(CH$_2$)$_5$C*H*$_3$)

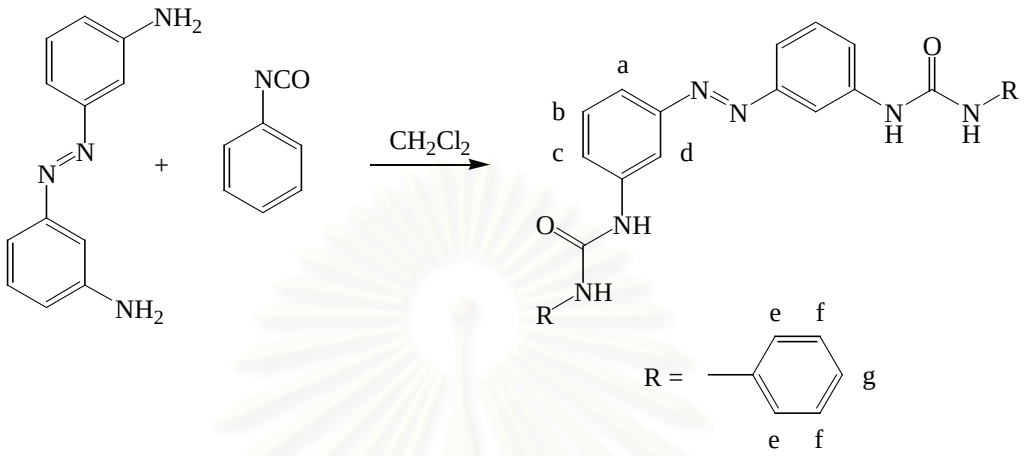
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{26}H_{38}O_2N_6 \cdot 0.5CH_2Cl_2 \cdot 1.5H_2O$ | C, 59.37; H, 7.90; N, 15.68 |
| Found | C, 59.35; H, 6.63; N, 16.42 |

**IR spectrum (KBr (cm$^{-1}$)):** 1640 (C=O)

**Melting point:** 121-124 °C

### 2.2.4 Preparation of 3,3′-bis(*N*′-phenylureido)azobenzene, 2c




**1** **2c**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, phenylisocyanate (0.28 mL, 2.56 mmol) was added to a stirred solution of 3,3′-diaminoazobenzene, **1**, (0.2120 g, 0.99 mmol) in dichloromethane (10 mL) and stirring was continued overnight at room temperature under of $N_2$. The precipitate was filtered and washed with dichloromethane. The solid was dissolved in a minimum amount of dimethylsulfoxide. Then, hexane and dichloromethane were added to precipipate a pale orange powder (0.2754 g, 62%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 2c:**

**$^1$H-NMR spectrum (DMSO-$d_6$):** δ (ppm) = 9.02 (s, 2H, -N=NArN*H*CONH-), 8.73 (s, 2H, -N=NArNHCON*H*-), 8.18 (s, 2H, -N=N*Ar*-$H_d$NH-), 7.61-7.32 (m, 8H, -N=N*Ar*-$H_aH_bH_c$NH- and -NH*Ar*-$H_e$), 7.25 (t, 4H, *J* = 8.14 Hz, -NH*Ar*-$H_f$), 6.98 (t, 2H, *J* = 8.14 Hz, -NH*Ar*-$H_g$)

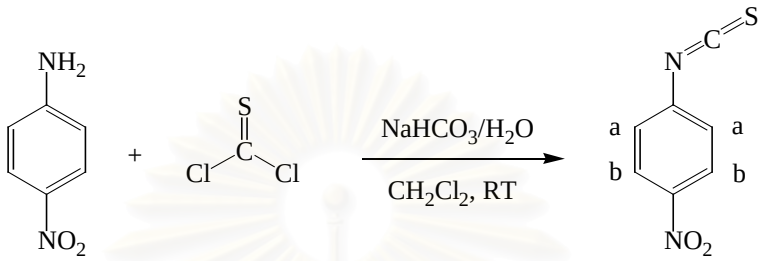
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{26}H_{22}O_6N_2$ | C, 69.32; H, 4.92; N, 18.66 |
| Found | C, 68.89; H, 5.00; N, 18.66 |

**IR spectrum (KBr ($cm^{-1}$)):** 1644 (C=O)

**Melting point**: 358-362 °C

### 2.2.5 Preparation of 4-nitrophenyl thioisocyanate, 3




**3**

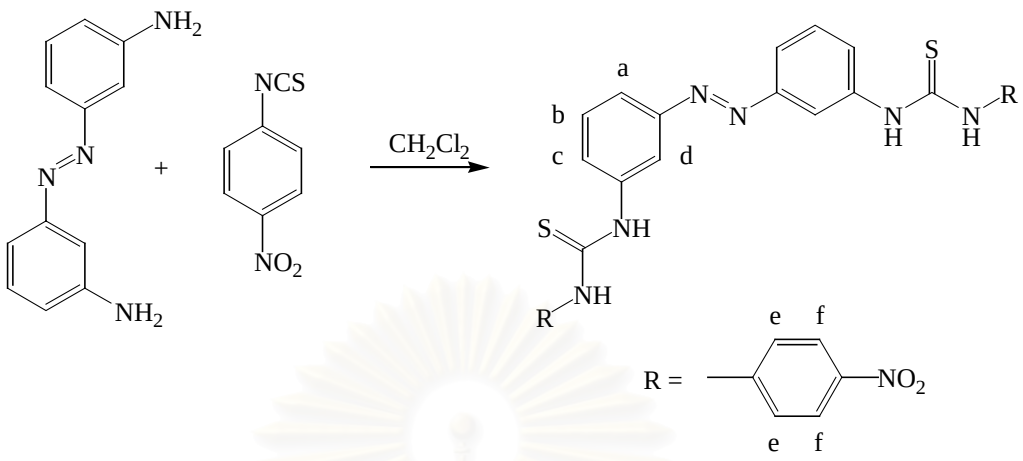
In a 250 mL one-necked round bottom flask equipped with a magnetic bar, 4-nitroaniline (2.1489 g, 15.56 mmol), a solution of sodium bicarbonate (2.9616 g, 35.25 mmol) in deionized water (30 mL) and dichloromethane (60 mL) were stirred for 10 minutes at room temperature. Thiophosgine (1.80 mL, 23.61 mmol) was added dropwise and the mixture was stirred overnight. The organic phase was separated and the aqueous layer was extracted with dichloromethane. The combined organic layer was washed with deionized water and dried over sodium sulfate anhydrous. After filtration of sodium sulfate, the solvent was evaporated under reduced pressure to give pure 4-nitrophenyl thioisocyanate, **3**, as a yellow solid (2.5982 g, 93%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 3:**

**$^1$H-NMR spectrum ($CDCl_3$):** δ (ppm) = 8.22 (d, 2H, *J* = 6.97 Hz, SCN*Ar*-$H_b$$NO_2$), 7.33 (d, 2H, *J* = 5.12 Hz, NCS*Ar*-$H_a$$NO_2$)

**Melting point:** 111-116 °C (lit.,[42] m.p. 112-113 °C)

### 2.2.6 Preparation of 3,3′-bis(*N*′-(4-nitrophenyl)thioureido)azobenzene, 2d




**1** **2d**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, a mixture of 3,3′-diaminoazobenzene, **1**, (0.4048 g, 1.91 mmol) and 4-nitrophenyl isothiocyanate, **3**, (0.8513 g, 4.72 mmol) in dichloromethane (20 mL) was stirred overnight at room temperature under nitrogen. Yellow solid precipitated from the solution. The solid was collected by fitration and washed with dichloromethane. The solid was recrystallized from hexane/dimethylsulfoxide/dichloromethane to give a pale yellow powder (0.5783 g, 56%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 2d:**

**$^1$H-NMR spectrum (DMSO-*d*$_6$):** δ (ppm) =10.64 (s, 2H, -N=NAr*NH*SONH-), 10.58 (s, 2H, -N=NArNHSO*NH*-), 8.53 (s, 2H, -N=N*Ar*-$H_d$NH-), 8.22 (d, 4H, *J* = 9.12 Hz, -NH*Ar*-$H_f$NO$_2$), 8.01 (dd, 2H, *J* = 8.24 Hz, -N=N*Ar*-$H_c$NH-), 7.92 (dd, 2H, *J* = 8.20 Hz, -N=N*Ar*-$H_a$NH-), 7.82 (d, 4H, *J* = 9.06 Hz, -NH*Ar*-$H_e$NO$_2$), 7.64 (t, 2H, *J* = 8.12 Hz, -N=N*Ar*-$H_b$NH-)

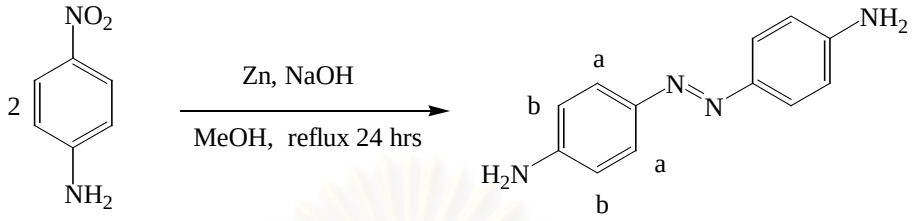
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{22}H_{30}O_6N_2 \cdot CH_2Cl_2$ | C, 49.32; H, 3.37; N, 17.04 |
| Found | C, 49.30; H, 3.23; N, 17.95 |

**IR spectrum (KBr (cm$^{-1}$)):** 1111 (C=S)

**Melting Point**: 183-186 °C

### 2.2.7 Preparation of 4,4′-diaminoazobenzene, 4




**4**

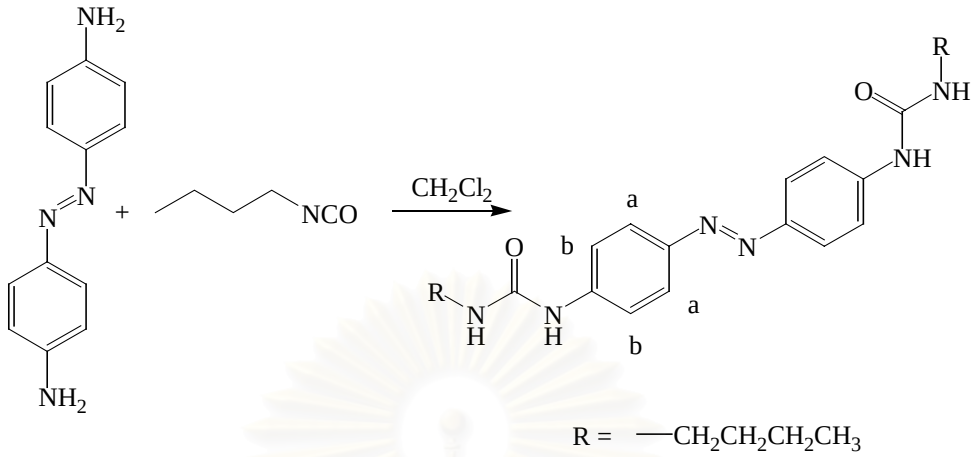
In a 250 mL two-necked round bottom flask equipped with a magnetic bar and a reflux condenser, a mixture of 4-nitroaniline (5.6984 g, 41.30 mmol) in methanol (100 mL), sodium hydroxide (6.4173 g, 160.40 mmol) in deionized water (50 mL) and zinc powder (5.6184 g, 86.59 mmol) was stirred. The reaction mixture was refluxed for 24 hours under of $N_2$. After the reaction was completed, the mixture was filtered while hot and the precipitate of sodium zincate was washed with a minimum amount of methanol. The combined filtrate was acidified with 3 M hydrochloric acid until the pH of the solution reached 7 and the then filtered. The solvent of filtrate was evaporated to give a yellow solid. The yellow solid was dissolved in dichloromethane and then mixed with silica gel and eluted through a silica gel column using dichloromethane as eluent to afford a bright yellow solid (3.1734 g, 36%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 4:**

**$^1$H-NMR spectrum ($CDCl_3$):** δ (ppm) = 8.05 (d, 4H, *J* = 9.02 Hz, -N=N*Ar*-$H_a$$NH_2$), 6.60 (d, 4H, *J* = 9.06 Hz, -N=N*Ar*-$H_b$$NH_2$); 4.38 (s, 4H, -ArN$H_2$)

**Melting point:** 115-118 °C

### 2.2.8 Preparation of 4,4′-bis(*N*′-butylureido)azobenzene, 5a




**4** **5a**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, 4,4′-diaminoazobenzene, **4**, (0.4112 g, 1.93 mmol) was dissolved in dichloromethane (20 mL) and *n*-butylisocyanate (0.44 mL, 4.99 mmol) was then added. The mixture was stirred overnight at room temperature under nitrogen atmosphere. After the reaction was completed, the solvent was evaporated by a rotary evaporator to obtain a yellow residue. The residue was redissolved in a minimum amount of dichloromethane and hexane was added to precipitate an off-white crystalline solid (6.298 g, 79%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 5a:**

**$^1$H-NMR spectrum ($CD_3CN$):** δ (ppm) = 8.09 (d, 4H, *J* = 5.05 Hz, -N=N*Ar*-$H_a$NH-), 7.73 (s, broad, 2H, -N=NArN*H*CONH-), 7.58 (d, 4H, *J* = 5.06 Hz, -N=N*Ar*-$H_b$NH-), 5.41 (s, broad, 2H, -N=NArNHCON*H*-), 3.15 (q, 4H, *J* = 5.92 Hz, -NHC$H_2$($CH_2$)$_2$$CH_3$)), 1.50-1.26 (m, 8H, -NHC$H_2$(C$H_2$)$_2$$CH_3$); 0.91 (t, 6H, *J* = 7.11 Hz, -NH($CH_2$)$_3$C$H_3$)

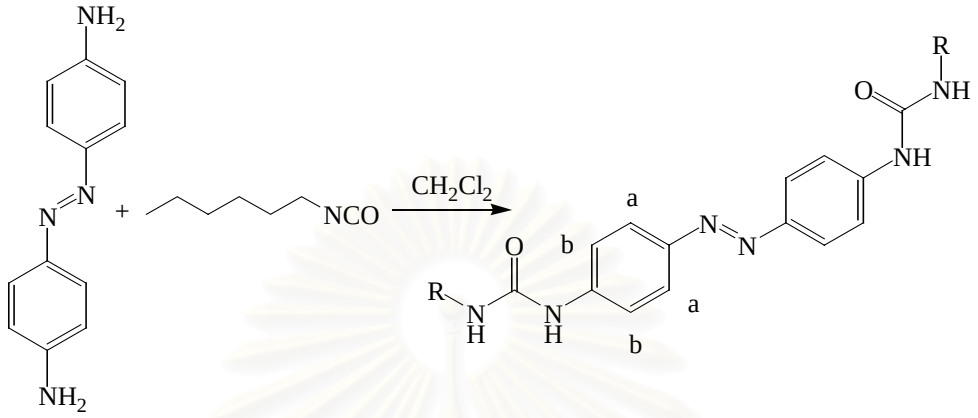
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{22}H_{30}O_6N_2$ | C, 64.37; H, 7.37; N, 20.47 |
| Found | C, 64.34; H, 7.17; N, 20.47 |

**IR spectrum (KBr ($cm^{-1}$)):** 1658 (C=O)

**Melting Point:** 115-118 °C

### 2.2.9 Preparation of 4,4′-bis(*N*′-hexylureido)azobenzene, 5b




**4** **5b**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, 4,4′-diaminoazobenzene, **4**, (0.2129 g, 1.00 mmol) was dissolved in dichloromethane (10 mL). Hexylisocyanate (0.28 mL, 2.50 mmol) was added dropwise and the reaction mixture was stirred overnight at room temperature under nitrogen atmosphere. After the reaction was completed, the solvent was concentrated on a rotary evaporator and precipitated with hexane to yield pure **5b** as a pale yellow crystalline solid (0.4059 g, 87%).The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 5b:**

**$^1$H-NMR spectrum ($CDCl_3$):** δ (ppm) = 8.11 (d, 4H, *J* = 5.05 Hz, -N=N*Ar*-$H_a$NH-), 7.78 (s, broad, 2H, -N=NArN*H*CONH-), 7.61 (d, 4H, *J* = 5.10 Hz, -N=N*Ar*-$H_b$NH-), 5.41 (s, broad, 2H, -N=NArNHCON*H*-), 3.15 (q, 4H, *J* = 5.97 Hz, -NHC$H_2$$(CH_2)_4CH_3$), 1.51-1.28 (m, 16H, -NHCH$_2$$(CH_2)_4CH_3$), 0.88 (t, 6H, *J* = 6.54 Hz, -NH$(CH_2)_5$C$H_3$)

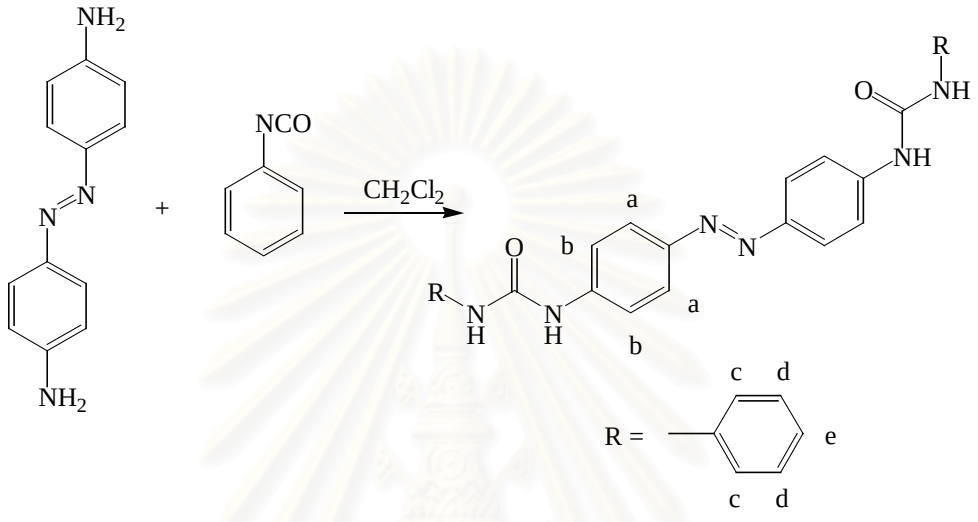
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{22}H_{30}O_6N_2 \cdot CH_2Cl_2$ | C, 58.80; H, 7.31; N, 15.68 |
| Found | C, 58.72; H, 6.28; N, 16.03 |

**IR spectrum (KBr ($cm^{-1}$)):** 1651 (C=O)

**Melting Point:** 109-114 °C

### 2.2.10 Preparation of 4,4′-bis(*N*′-phenylureido)azobenzene, 5c




**4** **5c**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, phenylisocyanate (0.28 mL, 2.56 mmol) was added into a stirred solution of 4,4′-diaminoazobenzene, **4**, (0.2130 g, 1.00 mmol ) in dichloromethane (10 mL). The reaction mixture was allowed to stir overnight at room temperature under nitrogen. The solution was evaporated to give a yellow residue. The residue was dissolved in a minimum amount of dimethylsulfoxide. Then, hexane and dichloromethane were added to precipitate an off-white crystalline solid (0.2812 g, 62%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 5c:**

**$^1$H-NMR spectrum (DMSO-$d_6$):** δ (ppm) = 9.42 (s, 2H, -N=NArN*H*CONH-), 8.91 (s, 2H, -N=NArNHCON*H*-), 8.18 (d, 4H, *J* = 7.33 Hz, -N=N*Ar*-$H_a$NH-), 7.68 (d, 4H, *J* = 7.31 Hz, -N=N*Ar*-$H_b$NH-), 7.46 (d, 4H, *J* = 8.88 Hz, -NH*Ar*-$H_c$), 7.29 (t, 4H, *J* = 7.88 Hz, -NH*Ar*-$H_d$), 7.01 (t, 2H, *J* = 7.37 Hz, -NH*Ar*-$H_e$)

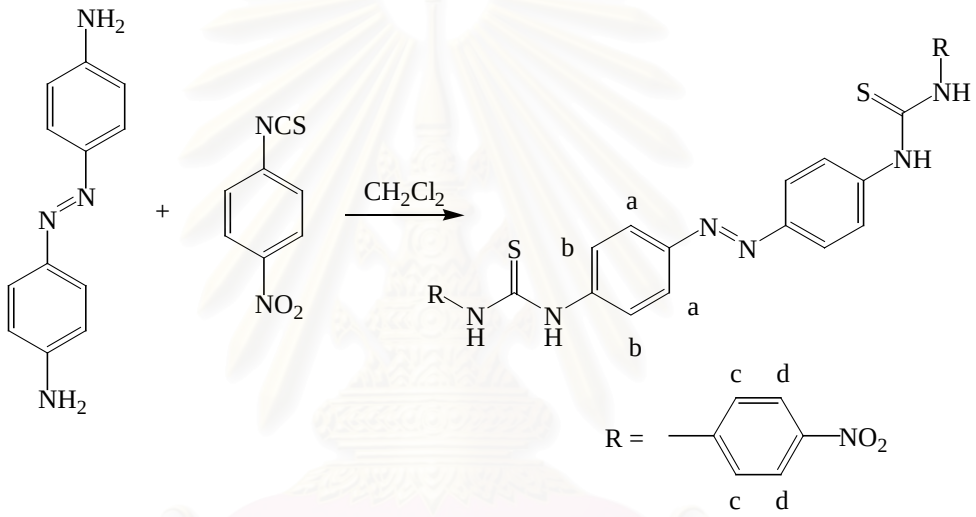
**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{26}H_{22}O_6N_2 \cdot CH_2Cl_2$ | C, 60.57; H, 4.52; N, 15.70 |
| Found | C, 60.40; H, 4.50; N, 16.17 |

**IR spectrum (KBr ($cm^{-1}$)):** 1649 (C=O)

**Melting point:** 214-217 °C

### 2.2.11 Preparation of 4,4′-bis(*N*′-(4-nitrophenyl)thioureido)azobenzene, 5d




**4** **5d**

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, a mixture of 4,4′-diaminoazobenzene, **4**, (0.4360 g, 2.05 mmol ) and 4-nitrophenyl thioisocyanate, **3**, (0.8932 g, 4.96 mmol) in dichloromethane (20 mL) was stirred overnight under an atmosphere of nitrogen at room temperature. The solvent was removed under reduced pressure. The residue was dissolved in a minimum amount of dimethylsulfoxide. Then, hexane and dichloromethane were added to precipipate an orange solid (0.6324 g, 57%). The product was dried in *vacuo* and kept in a desiccator.

**Characterization data for 5d:**

**$^1$H-NMR spectrum (DMSO-$d_6$):** δ (ppm) = 10.76 (s, 4H, -N=NArN*H*CSN*H*-), 8.23 (d, 4H, *J* = 9.08 Hz, -N=N*Ar*-$H_a$NH- and -NH*Ar*-$H_d$$NO_2$), 7.83 (d, 4H, *J* = 9.08 Hz, -N=N*Ar*-$H_b$NH- and -NH*Ar*-$H_c$$NO_2$)

**Elemental analysis:**

| | |
|---|---|
| Anal. Caled for $C_{22}H_{30}O_6N_2 \cdot CH_2Cl_2 \cdot 2H_2O$ | C, 46.76; H, 3.78; N, 16.16 |
| Found | C, 46.77; H, 3.70; N, 15.73 |

**IR spectrum (KBr ($cm^{-1}$)): 1117 (C=S)**

**Melting point**: 196-199 **°C**

### 2.2.12 Preparation of tetrabutylammonium salts

In a 50 mL two-necked round bottom flask equipped with a magnetic bar, 0.8 M solution of tetrabutylammoniun hydroxide in methanol (5.0 mL, 4.00 mmol) was added to a stirred solution of a dicarboxylic acid (2.00 mmol) in methanol (15 mL) and stirring was continued overnight at room temperature under nitrogen atmosphere. The solvent was evaporated and the solid was dried for several days under high vacuum over $P_2O_5$. The resulting tetrabutylammonium salts was stored under anhydrous condition before use.

## 2.3 Complexation studies

### 2.3.1 $^1$H-NMR titration studies for complexes of ligands 2b and 5a with anion guests

Typically, a 0.01 M solution of a ligand (5.0 x $10^{-6}$ mol) in $CD_3CN$ (0.5 mL) was prepared in a 5-mm NMR tube. An initial $^1$H-NMR spectrum of the solution of the ligand was recorded. A 0.1 M stock solution of guest molecules (3.0 x $10^{-5}$ mol) in $CD_3CN$ (0.3 mL) was prepared in a vial (shown in Table 2.1). The solution of a guest

molecule was added *via* microsyringe (10 μL portions) to the NMR tube. $^{1}$H-NMR spectra were recorded after each addition.

**Table 2.1** Amounts of tetrabutylammonium salts that used in anion complexation studies with ligands **2b** and **5a**.

| Ligands | Tetrabutylammonium anions | Weight (gram) |
|---|---|---|
| **2b or 5a** | $CH_3COO^-$ | 0.0090 |
| | $^-OOCCOO^-$ | 0.0172 |
| | $^-OOCCH_2COO^-$ | 0.0176 |
| | $^-OOC(CH_2)_2COO^-$ | 0.0180 |
| | $^-OOC(CH_2)_3COO^-$ | 0.0185 |
| | $^-OOC(CH_2)_4COO^-$ | 0.0189 |
| | $^-OOC(CH_2)_5COO^-$ | 0.0193 |
| | $^-OOC(CH_2)_6COO^-$ | 0.0197 |
| | $^-OOC(CH_2)_7COO^-$ | 0.0201 |

### 2.3.2 UV-vis titration studies for complexes of ligand 2d with anion guests

Typically, a stock solution of 0.001 M solution of a ligand **2d** ($5.0 \times 10^{-6}$ mol) in 5 mL of DMSO (AR grade) was prepared in a volumetric flask. 0.25 mL of 0.001 M stock solution of ligand **2d** was pipetted into a 10 mL volumetric flask and the solution was adjusted to the marked volume with DMSO. 2 mL of $2.5 \times 10^{-5}$ M stock solution of ligand **2d** was pipetted into a 1 cm pathlength quartz cuvette and absorption spectrum of **2d** was recorded from 260 to 650 nm at room temperature with a Varian Cary 50 UV-vis spectrophotometer. A solution of a guest in DMSO was prepared in a 25 mL volumetric flask (shown in Table 2.2). The solution of a guest was added directly to the cuvette by microburette and stirred for 30 sec and absorption spectra of solution was recorded after each addition until absorbance of a new peak at 400 nm was constant.

**Table 2.2** Amounts of tetrabutylammonium salts that used in anion complexation studies with ligand **2d**.

| Ligand | Tetrabutylammonium anions | Weight (gram) |
|---|---|---|
| **2d** | $CH_3COO^-$ | 0.0075 |
| | $^-OOCCOO^-$ | 0.0358 |
| | $^-OOCCH_2COO^-$ | 0.0367 |
| | $^-OOC(CH_2)_2COO^-$ | 0.0376 |
| | $^-OOC(CH_2)_3COO^-$ | 0.0154 |
| | $^-OOC(CH_2)_4COO^-$ | 0.0393 |
| | $^-OOC(CH_2)_5COO^-$ | 0.0160 |
| | $^-OOC(CH_2)_6COO^-$ | 0.0164 |
| | $^-OOC(CH_2)_7COO^-$ | 0.0168 |

### 2.3.2 UV-vis titration studies for complexes of ligand 5d with anion guests

Typically, a stock solution of 0.001 M solution of a ligand **5d** ($5.0 \times 10^{-6}$ mol) in 5 mL of DMSO (AR grade) was prepared in a volumetric flask. 0.15 mL of 0.001 M stock solution of ligand **5d** was pipetted into a 10 mL volumetric flask and the solution was adjusted to the marked volume with DMSO. 2 mL of $1.5 \times 10^{-5}$ M stock solution of ligand **5d** was pipetted into a 1 cm pathlength quartz cuvette and absorption spectrum of **5d** was recorded from 260 to 550 nm at room temperature with a Varian Cary 50 UV-vis spectrophotometer. A solution of a guest in DMSO was prepared in a 25 mL volumetric flask (shown in Table 2.3). The solution of a guest was added directly to the cuvette by microburette and stirred for 30 sec and absorption spectra of solution was recorded after each addition until absorbance of a new peak at 407 nm was constant.

**Table 2.3** Amounts of tetrabutylammonium salts that used in anion complexation studies with ligand **5d**.

| Ligand | Tetrabutylammonium anions | Weight (gram) |
|---|---|---|
| **5d** | $CH_3COO^-$ | 0.0113 |
| | $^-OOCCOO^-$ | 0.0215 |
| | $^-OOCCH_2COO^-$ | 0.0220 |
| | $^-OOC(CH_2)_2COO^-$ | 0.0090 |
| | $^-OOC(CH_2)_3COO^-$ | 0.0092 |
| | $^-OOC(CH_2)_4COO^-$ | 0.0236 |
| | $^-OOC(CH_2)_5COO^-$ | 0.0096 |
| | $^-OOC(CH_2)_6COO^-$ | 0.0098 |
| | $^-OOC(CH_2)_7COO^-$ | 0.0100 |

### 2.3.4 Photoirradiation studies

#### 2.3.4.1 $^1$H-NMR titration studies for complexes of ligands 2b and 5a (after irradiation) with anion guests

Typically, a 0.01 M solution of a ligand ($5.0 \times 10^{-6}$ mol) in $CD_3CN$ (0.5 mL) was prepared in a 5-mm NMR tube and was irradiated with a 450 W medium pressure Hg lamp at room temperature for 15 minutes. The distance from the Hg lamp to the sample tube was 5 cm. Then, $^1$H-NMR spectrum was recorded. A 0.1 M stock solution of guest molecules ($3.0 \times 10^{-5}$ mol) in $CD_3CN$ (0.3 mL) was prepared (shown in Table 2.1) and then added *via* microsyringe (10 μL portions) to the NMR tube after photoirradiation. $^1$H-NMR spectra were recorded after each addition.

**2.3.4.2 UV-vis titration studies for complexes of ligands 2d and 5d (after irradiation) with anion guests**

Typically, a stock solution of 3.0 x $10^{-5}$ M solution of a ligand (1.5 x $10^{-6}$ mol) in DMSO (AR grade) was prepared by pipetting 1.50 mL of 1.0 x $10^{-3}$ M stock solution into 50 mL volumetric flask and making up to the marked volume with DMSO. 2 mL of 3.0 x $10^{-5}$ M stock solution of ligand was pipetted into a 1 cm pathlength quartz cuvette and absorption spectra of ligand was recorded from 260 to 600 nm at room temperature with a Varian Cary 50 UV-vis spectrophotometer. Then, 25 mL of 3.0 x $10^{-5}$ M stock solution of ligand was transferred into a tube and irradiated with a 450 W medium pressure Hg lamp at room temperature for 15 minutes. The distance between the lamp and the sample tube was 5 cm. After irradiation, 2 mL of solution was pipetted into a 1 cm pathlength guartz cuvette and the electronic absorption spectra of solution was recorded at wavelengths between 260-650 nm. A 1.5 x $10^{-3}$ M stock solution of guest (3.75 x $10^{-5}$ mol) in 25 mL of DMSO was prepared in a volumetric flask (shown in Table 2.4). The solution of a guest was added directly to the cuvette by a microburette (200 μL portions) and stirred for 30 sec and absorption spectra of the solution were recorded after each addition. The change in absorbance with solution of a guest was followed until the absorbance of a new peak was constant.

**Table 2.4** Amounts of tetrabutylammonium salts that used in anion complexation studies with ligands **2d** and **5d** (after irradiation).

| Ligands | Tetrabutylammonium anions | Weight (gram) |
|---|---|---|
| **2d or 5d** | $CH_3COO^-$ | 0.0113 |
| | $^-OOCCOO^-$ | 0.0215 |
| | $^-OOCCH_2COO^-$ | 0.0220 |
| | $^-OOC(CH_2)_2COO^-$ | 0.0225 |
| | $^-OOC(CH_2)_3COO^-$ | 0.0231 |
| | $^-OOC(CH_2)_4COO^-$ | 0.0236 |
| | $^-OOC(CH_2)_5COO^-$ | 0.0241 |
| | $^-OOC(CH_2)_6COO^-$ | 0.0246 |
| | $^-OOC(CH_2)_7COO^-$ | 0.0252 |

# CHAPTER III

# RESULTS AND DISCUSSION

## 3.1 Synthesis and characterization of azobenzene derivatives

### 3.1.1 Synthesis and characterization of 3,3′-diaminoazobenzene derivatives

Synthesis of compounds **2a** to **2d** are outlined in Figure 3.1. A reductive coupling reaction was carried out following the literature procedure.[41] In the first step 3,3′-diaminoazobenzene, **1**, was prepared by reductive coupling of two units of 3-nitroaniline in methanol in the presence of aqueous sodium hydroxide and zinc (2.2 equiv.) and refluxed under nitrogen for 10 hours. The desired product was separated on a silica gel column with 20% ethyl acetate/dichloromethane as eluent to give compound **1** in 61% yield as a bright yellow solid. The $^{1}$H-NMR spectrum of **1** showed the presence of amine protons signal at 3.96 ppm. The aromatic protons appeared as two doublets at 7.53 and 6.93 ppm and two triplets at 7.47 and 7.26 ppm. Subsequently, the coupling reaction of **1** with 2.5 equiv. of *n*-butylisocyanate in dichloromethane was performed under nitrogen at room temperature overnight. After recrystallization in dimethylsulfoxide with dichloromethane and hexane, compound **2a** was obtained in 77% yield as a pale orange solid. The $^{1}$H-NMR spectrum of **2a** showed characteristic peaks of butyl group as a quartet at 3.09 ppm ($J$ = 5.9 Hz) and a multiplet at 1.43-1.22 ppm and a triplet of methyl groups at 0.89 ppm ($J$ = 7.1 Hz). IR spectra showed a C=O stretching band at 1635 cm$^{-1}$.

Compound **2b** was synthesized by a coupling reaction of compound **1** with 2.4 equiv. of hexylisocyanate in dichloromethane. After stirring overnight, the solid precipitated from reaction was recrystallized with dichloromethane and hexane to afford compound **2b** as a white crystalline solid in 92% yield. The $^{1}$H-NMR spectrum of **2b** exhibited two broad peaks due to urea protons (-N=NArN*H*CON*H*-) at 7.53 and

5.43 ppm with an integral ratio of 1:1. The hexyl protons (-NHC$H_2$(C$H_2$)$_4$C$H_3$) appeared as a quartet at 3.15 ppm, a multiplet at 1.51-1.28 ppm and a triplet of methyl groups at 0.88 ppm. IR spectra showed a C=O stretching band at 1640 cm$^{-1}$.

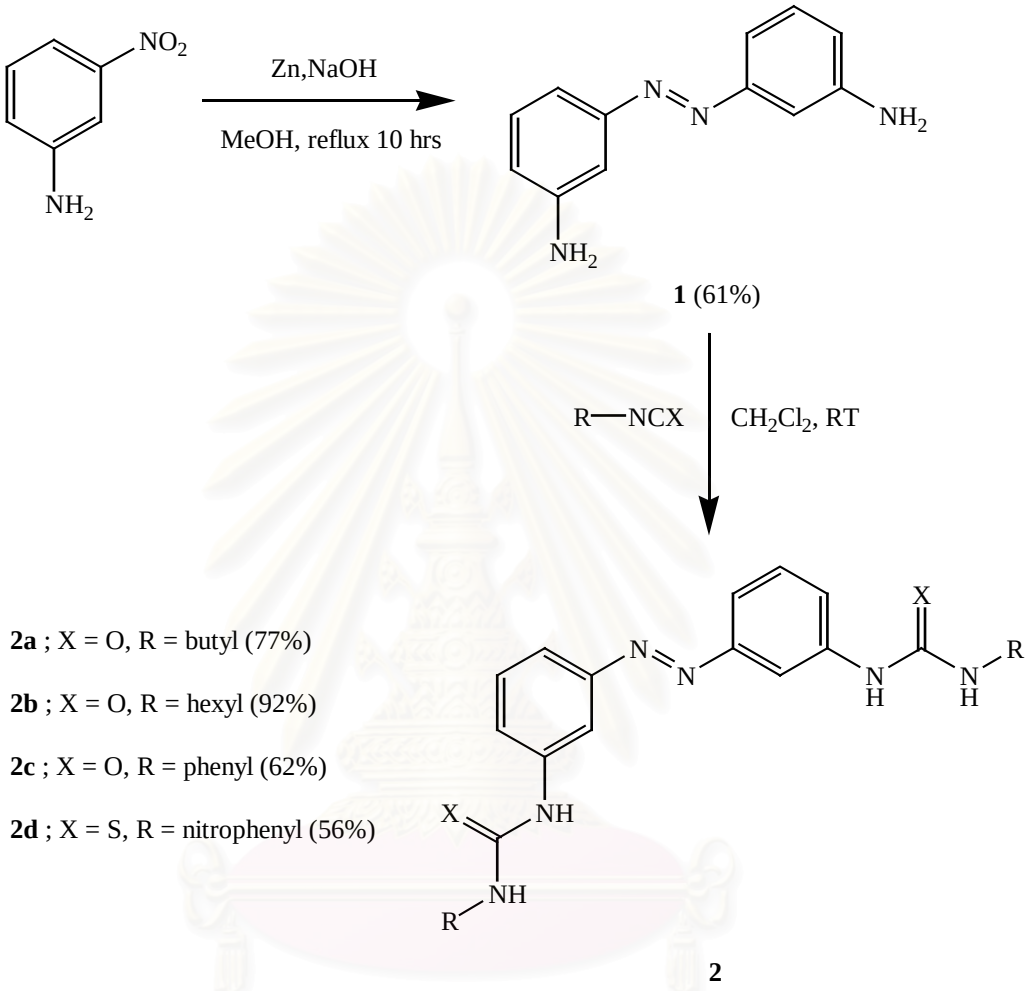
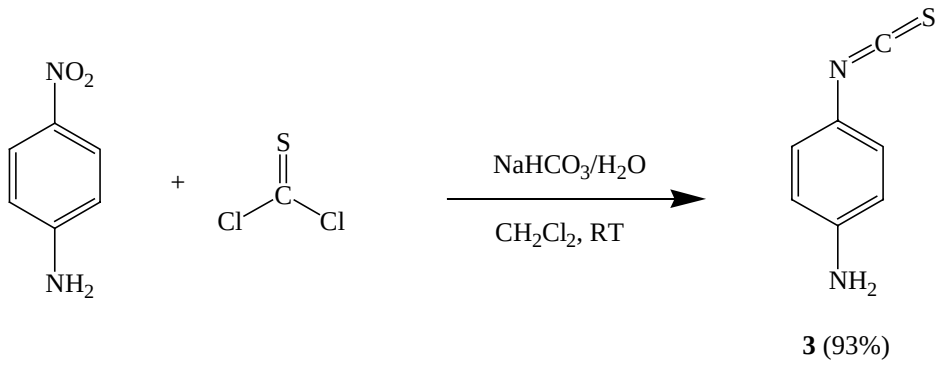



**Figure 3.1** Synthetic pathway of 3,3$^{/}$-diaminoazobenzene derivatives (**2a**-**2d**).

A coupling reaction between **1** and phenylisocyanate (2.5 equiv.) in dichloromethane was done under nitrogen at room temperature overnight. After recrystallization in dimethylsulfoxide with dichloromethane and hexane, compound **2c** was obtained as a pale orange powder in 62% yield. The $^1$H-NMR spectrum of **3a** was shown in Figure A.4. Aromatic protons appeared at 8.18-6.98 ppm while NH-urea signals appeared at 9.02 and 8.73 ppm. IR spectra showed a C=O stretching band at 1644 cm$^{-1}$.




**3** (93%)

**Figure 3.2** Synthesis of 4-nitrophenyl thioisocyanate, **3**.

4-Nitroaniline was reacted with 1.5 equiv. of thiophosgine in the presence of 2.3 equiv. of sodium bicarbonate in dichloromethane at room temperature overnight (Figure 3.2). A yellow solid of 4-nitrophenyl thioisocyanate, **3**, was obtained in 93% yield. The structure was confirmed by $^{1}$H-NMR and IR spectroscopy, which are in accordance with the literature.[42]

Compound **2d** was synthesized by a coupling reaction of **1** with 2.5 equiv. of 4-nitrophenyl thioisocyanate, **3**, in dichloromethane. Compound **2d** was purified by crystallization in dimethylsulfoxide and dichloromethane/hexane to afford a pale yellow powder of **2d** (56%). The $^{1}$H-NMR spectrum of **2d** showed two singlet peaks due to NH-thiourea at 10.64 and 10.58 ppm. Aromatic protons appeared at 8.53-7.64 ppm. IR spectra showed a C=S stretching band at 1111 cm$^{-1}$.

### 3.1.2 Synthesis and characterization of 4,4′-diaminoazobenzene derivatives

The synthetic pathway of 4,4′-diaminoazobenzene are shown in Figure 3.3. A reductive coupling of 4-nitroaniline with 2.2 equiv. of zinc in the presence of sodium hydroxide solution in methanol. Purification of the crude product by silica gel column chromatography with dichloromethane as an eluent gave a bright yellow solid, compound **4**, in 36% yield. The $^{1}$H-NMR spectrum of **4** showed two doublet signals of aromatic protons at 8.05 and 6.06 ppm ($J$ = 9.0 and 9.0 Hz, respectively). The broad peak at 4.38 ppm corresponded to amine protons.

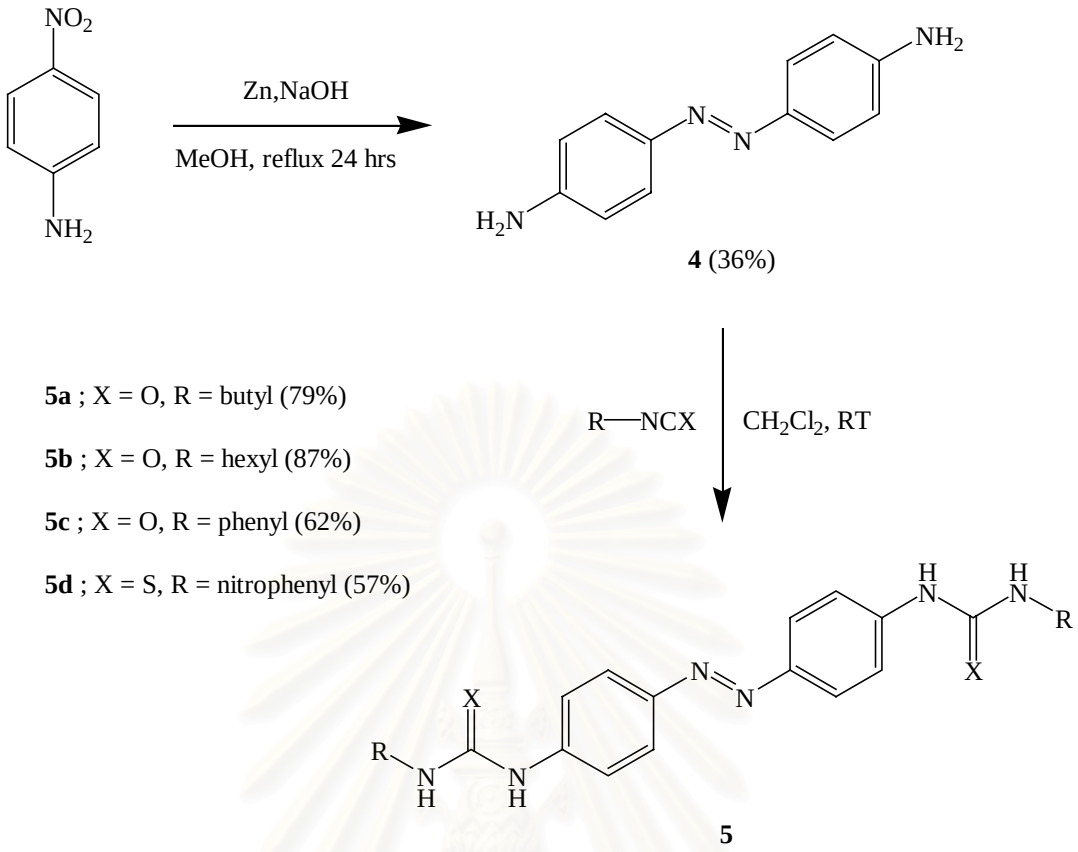



**Figure 3.3** Synthetic pathway of 4,4′-diaminoazobenzene derivatives (**5a**-**5d**).

A coupling reaction of 2.5 equiv. of *n*-butylisocyanate with 4,4′-diaminoazobenzene, **4**, was carried out in dichloromethane for 12 hours. Compound **5a** was obtained with 79% yield as an off-white crystalline solid after precipitation with hexane. The $^{1}$H-NMR showed the characteristic peaks of butyl group, a quartet at 3.15 ppm ($J$ = 5.9, 5.9 Hz) and a multiplet at 1.51-1.28 ppm and a triplet of methyl groups at 0.88 ppm ($J$ = 6.5 Hz). In addition, the urea protons of **5a** showed as two broad signals at 7.78 and 5.41 ppm for -N=NArN*H*CON*H*-. IR spectra showed a C=O stretching band at 1658 cm$^{-1}$.

A coupling reaction of 4,4′-diaminoazobenzene, **4**, with 2.5 equiv. of hexylisocyanate in dichloromethane was done under nitrogen at room temperature for 12 hours. Compound **5b** was crystallized in dichloromethane and hexane to give a yellow crystalline solid in 87% yield. The $^{1}$H-NMR spectrum of **5b** exhibited two broad peaks due to urea protons (-N=NArN*H*CON*H*-) at 7.78 and 5.41 ppm with integral ratio of 1:1. The hexyl protons (-NHC$H_2$(C$H_2$)$_4$C$H_3$) appeared as a quartet at

3.15 ppm, a multiplet at 1.51-1.28 ppm and a triplet of methyl groups at 0.88 ppm. IR spectra showed a C=O stretching band at 1651 $cm^{-1}$.

Compound **5c** was prepared from a coupling reaction of compound **4** with 2.5 equiv. of phenylisocyanate in dichloromethane for 12 hours. An off-white crystalline solid product, **5c,** was obtained in 62% yield. The $^1$H-NMR spectrum of **5c** exhibited aromatic proton signals at 8.18-7.01 ppm. The NH-urea signals appeared at 9.42 and 8.91 ppm. IR spectra showed a C=O stretching band at 1649 $cm^{-1}$.

Compound **5d** was synthesized by a coupling reaction of compound **4** with 2.4 equiv. of 4-nitrophenyl thioisocyanate, **3**, in dichloromethane for 12 hours. An orange solid of compound **5d** was obtained in 57% yield. The $^1$H-NMR spectrum of **5d** showed only one singlet signal of -N=NArN*H*SON*H*- at 10.76 ppm. Due to the N-donor at *para* position on phenyl groups, both NH-thiourea protons were equivalent. The two doublet signals of aromatic protons at 8.23 and 7.83 ppm were shifted downfield (aromatic protons of the starting material appeared at 8.05 and 6.60 ppm). IR spectra showed a C=S stretching band at 1117 $cm^{-1}$.

**3.2 Anion complexation studies**

Compounds **2b**, **2d**, **5a** and **5d** contain four urea or thiourea NH groups as hydrogen bond donors for binding dicarboxylate anions ($^-O_2C(CH_2)_nCO_2^-$). Four compounds have different position of urea group in azobenzene derivatives suitable for recognition studies with dicarboxylate anions having various chain lengths. Thus, complexation studies of compounds **2b**, **2d**, **5a** and **5d** with dicarboxylate anions such as tetrabutylammonium (TBA) acetate, oxalate, malonate, succinate, glutarate, adipate, pimelate, suberate and azelate were carried out.

Compounds **2d** and **5a** possessed alkyl chains and this made **2d** and **5a** soluble in aprotic solvents such as $CD_3CN$ and $CDCl_3$. Nevertheless, they also dissolved in protic solvents such as $CH_3OH$ and DMSO-$d_6$. Hydrogen bonding plays a particularly important role in interactions between anions and protic solvents. Hence, protic solvents were good anion solvators due to the small size of hydrogen atom. When $CDCl_3$ was used as a solvent, NH signals of the urea group of **2d** and **5a** became

broad upon the addition of dicarboxylate anions in $CDCl_3$. Association constants cannot be calculated using $CDCl_3$. Therefore, $CD_3CN$ was used instead.

Compounds **2d** and **5d** consisted of azobenzene and *p*-nitrophenylthiourea moieties as two different chromophores. The anion recognition *via* hydrogen-bonding interactions can also be easily monitored by anion-complexation induced change in UV-vis absorption spectra and with the naked eye. From results of $^1$H-NMR and UV-vis titrations association constants can be calculated.

### 3.2.1 Complexation studies of compounds 2b and 5a with various dicarboxylate anions by $^1$H-NMR spectrophotometry

$^1$H-NMR spectra of compounds **2b** and **5a** with and without dicarboxylate anions in $CD_3CN$ at room temperature were recorded. The $^1$H-NMR spectrum of compound **2b** showed a broad signal at 5.32 ppm due to the NH proton of one urea group and a signal at 7.50 ppm due to the NH proton that was adjacent to the aromatic ring while two N*H* signals of compound **5a** showed at 5.39 and 7.69 ppm. Upon addition of dicarboxylate anions, both signals of the NH protons shifted remarkably downfield as shown in Tables 3.1 and 3.2. The data in Tables 3.1 and 3.2 indicated that all carboxylate anions form complexes with compounds **2b** and **5a** *via* hydrogen-bonding interactions between the urea and carboxylate groups. For example, all NH signals in $^1$H-NMR spectra of titrations between **2b** and **5a** with suberate shifted downfield as shown in Figures 3.4 and 3.5.

**Table 3.1** $^{1}$H-NMR chemical shifts (ppm) for compound **2b** (in $CD_3CN$) in the absence and presence of dicarboxylate anions.

| Anions | $H_A$ | $H_B$ |
|---|---|---|
| None | 7.50 | 5.32 |
| Acetate | 11.62 | 8.99 |
| Oxalate | 11.47 | 8.80 |
| Malonate | 11.39 | 8.74 |
| Succinate | 10.49 | 7.47 |
| Glutarate | 11.48 | 8.89 |
| Adipate | 11.55 | 8.88 |
| Pimelate | 11.55 | 8.85 |
| Suberate | 11.72 | 9.05 |
| Azelate | 11.57 | 8.89 |

**Table 3.2** $^{1}$H-NMR chemical shifts (ppm) for compound **5a** (in $CD_3CN$) in the absence and presence of dicarboxylate anions.

| Anions | $H_A$ | $H_B$ |
|---|---|---|
| None | 7.69 | 5.39 |
| Acetate | 11.70 | 9.02 |
| Oxalate | [a] | 9.07 |
| Malonate | 11.75 | 9.06 |
| Succinate | 10.76 | 7.63 |
| Glutarate | 11.43 | 8.51 |
| Adipate | 11.98 | 9.20 |
| Pimelate | 11.79 | 8.98 |
| Suberate | 12.10 | 9.33 |
| Azelate | 11.95 | 9.16 |

[a] N$H_A$ signal could not be observed.

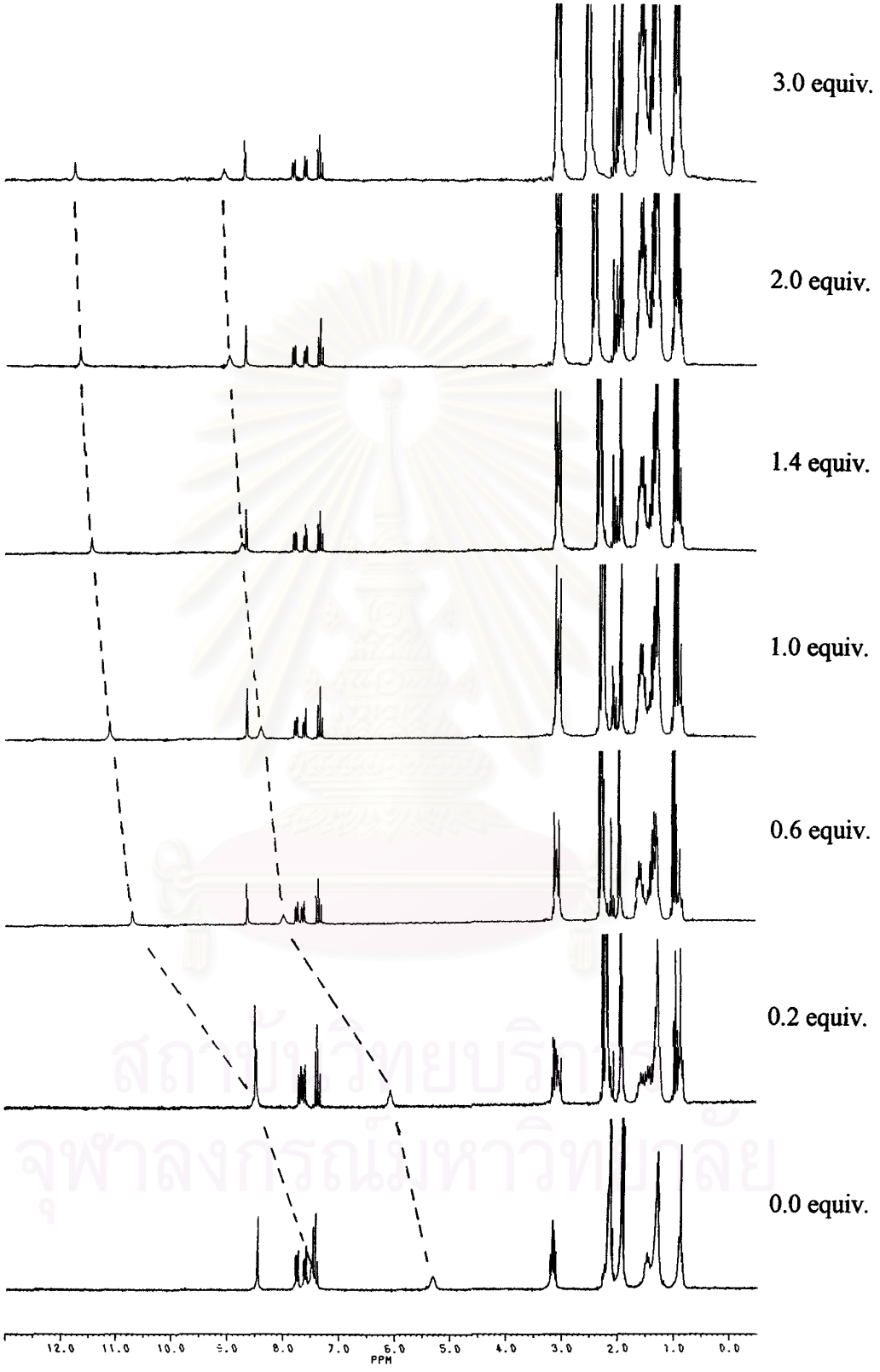



**Figure 3.4** $^{1}$H-NMR spectra of **2b** and suberate in $CD_3CN$ with 200 MHz.

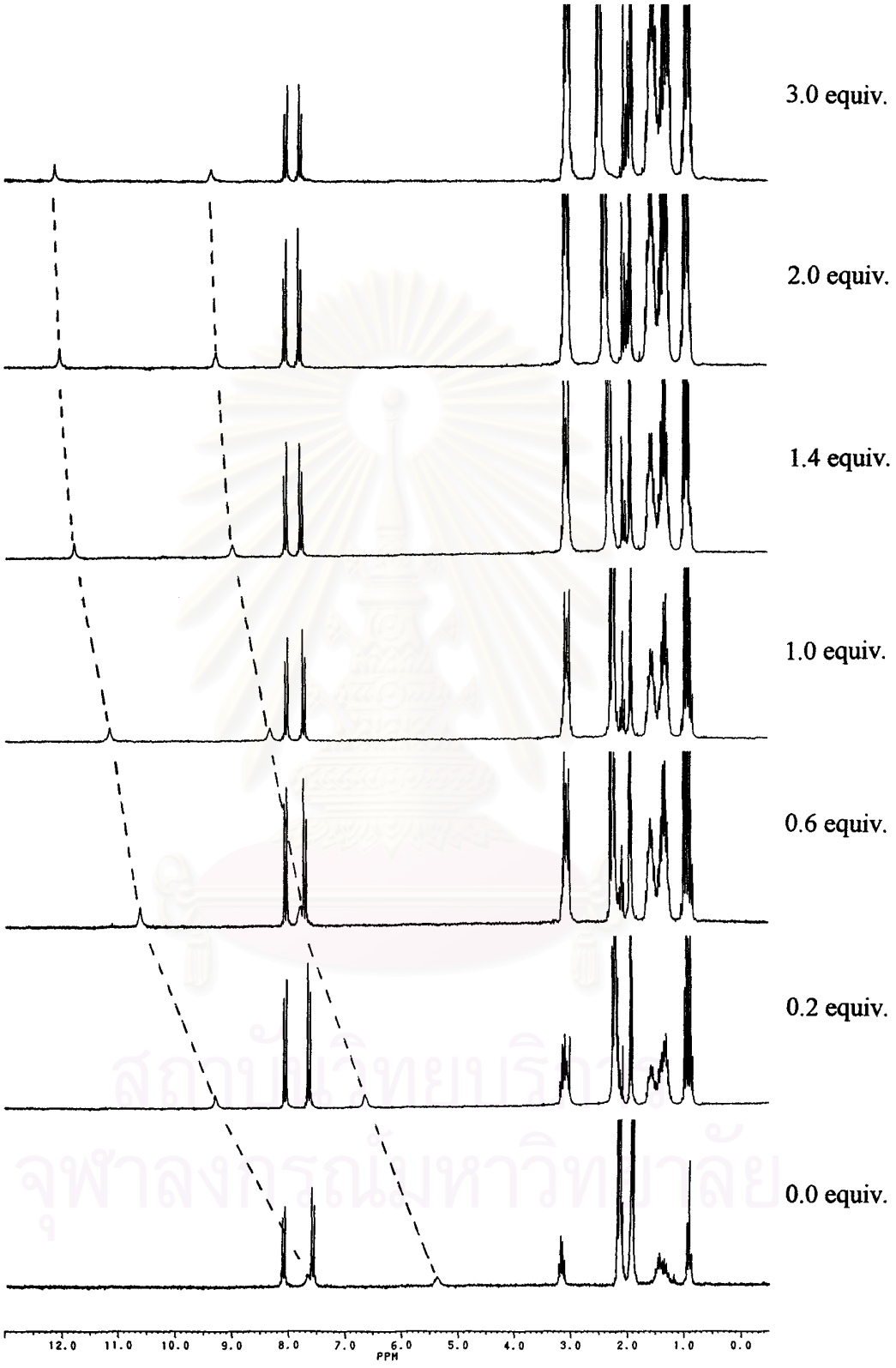



**Figure 3.5** $^{1}$H-NMR spectra of **5a** and suberate in $CD_3CN$ with 200 MHz.

Addition of more than 1.0 equiv. of dicarboxylate anions showed a slight downfield shift of the NH protons, indicated that **2b** and **5a** formed complexes with dicarboxylate anions in a 1:1 stoichiometry (Figures 3.6 and 3.7). In addition, the 1:1 stoichiometry for receptors and dicarboxylate anions was confirmed by Job's plots[43] (Figure 3.8 and 3.9).

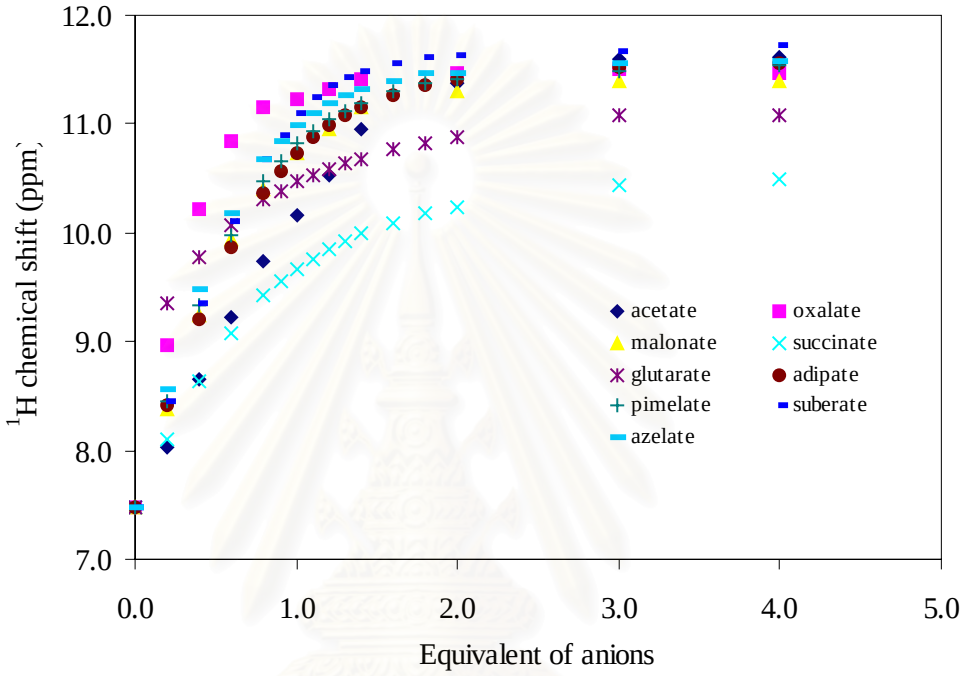



**Figure 3.6** Titration curves between **2b** (N$H_A$) and various dicarboxylate anions in $CD_3CN$.

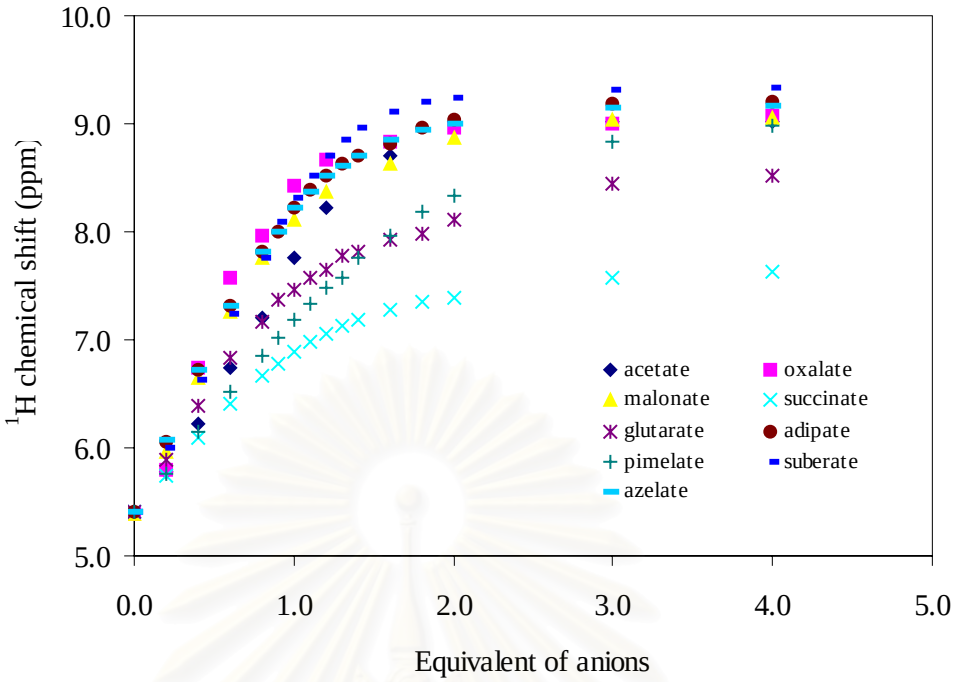



**Figure 3.7** Titration curves between **5a** (N$H_B$) and various dicarboxylate anions in $CD_3CN$.

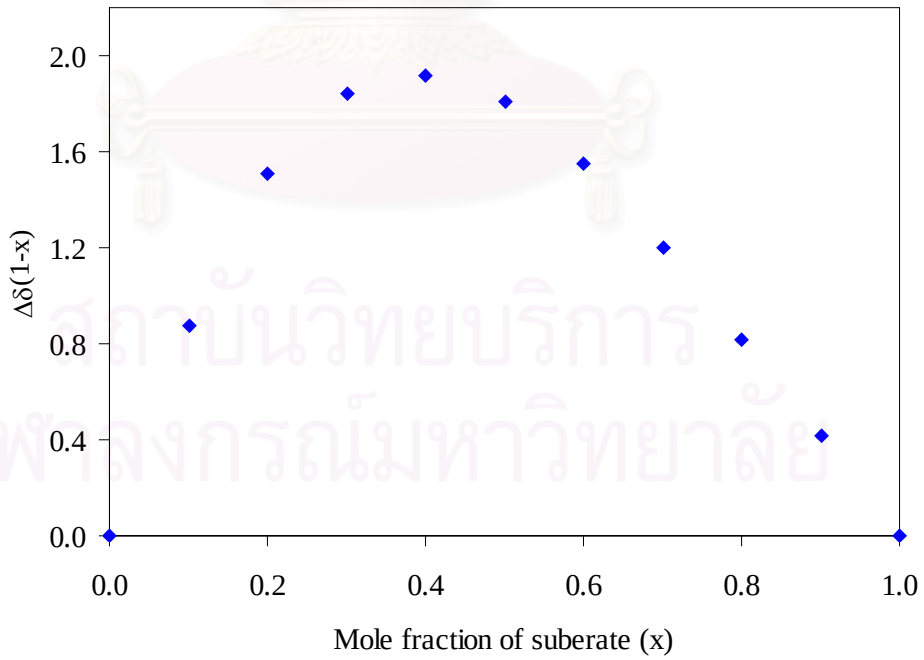



**Figure 3.8** The Job's plot of compound **2b** (N$H_A$) with suberate.

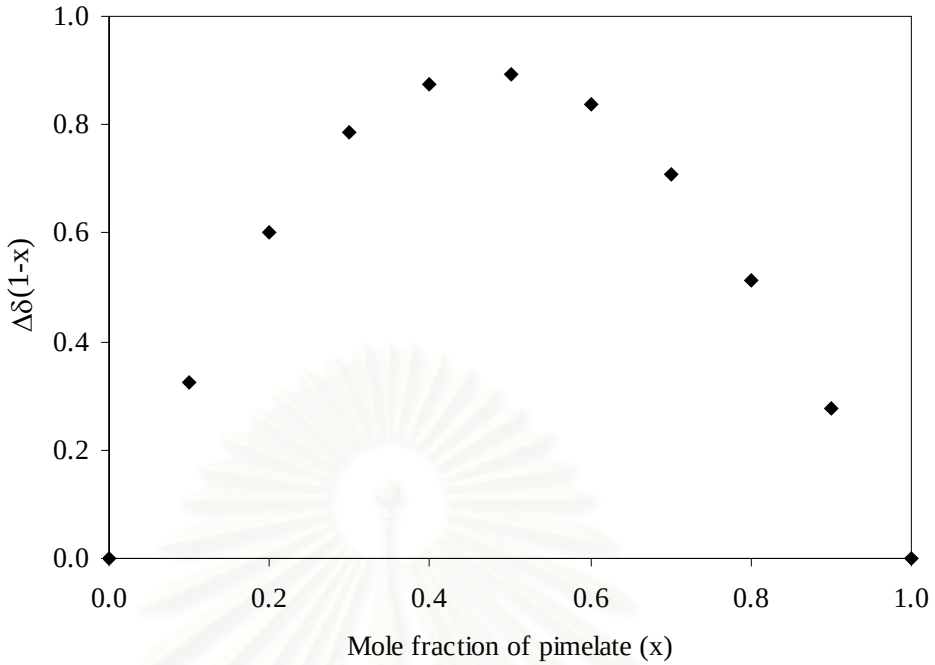



**Figure 3.9** The Job's plot of compound **5a** (N$H_B$) with pimelate.

Binding constants of dicarboxylate anions to the compounds **2b** and **5a** were obtained from the resulting titration curves using the EQNMR computer program[44] and values were presented in Table 3.3.

**Table 3.3** Binding constants of compounds **2b** and **5a** toward various dicarboxylate anions.

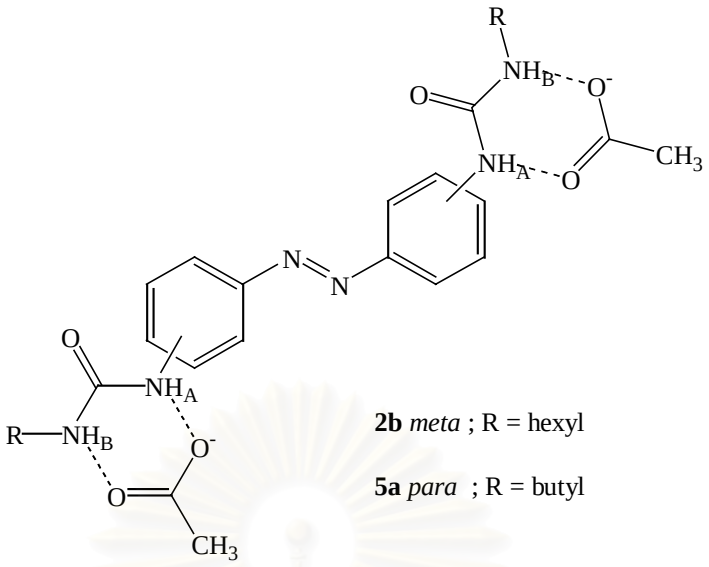
| Anions | Compound **2b** | Compound **5a** |
|---|---|---|
| Acetate | [b] | [b] |
| Oxalate | 6875 | 2809[c] |
| Malonate | 2241 | 1956 |
| Succinate | 644 | 509 |
| Glutarate | 516 | 617 |
| Adipate | 1418 | 1416 |
| Pimelate | 1876 | 197 |
| Suberate | 3207 | 1464 |
| Azelate | 2974 | 1461 |

[b] Binding constants cannot be calculated.

[c] Calculated from the change in chemical shift of N$H_B$.

In addition, compounds **2b** and **5a** possess the azobenzene groups which can undergo photoinduced *cis-trans* isomerization. Compounds **2b** and **5a** exist in the *trans* isomer in solution at room temperature because the *trans* isomer of azobenzene was thermodynamically more stable than the *cis* isomer. The Job's plot of acetate showed a maximum when the mol fraction was 0.60, which indicated 2:1 guest-host stoichiometry. A possible structure for the complex between compounds **2b** and **5a** with acetate is shown in Figure 3.10.

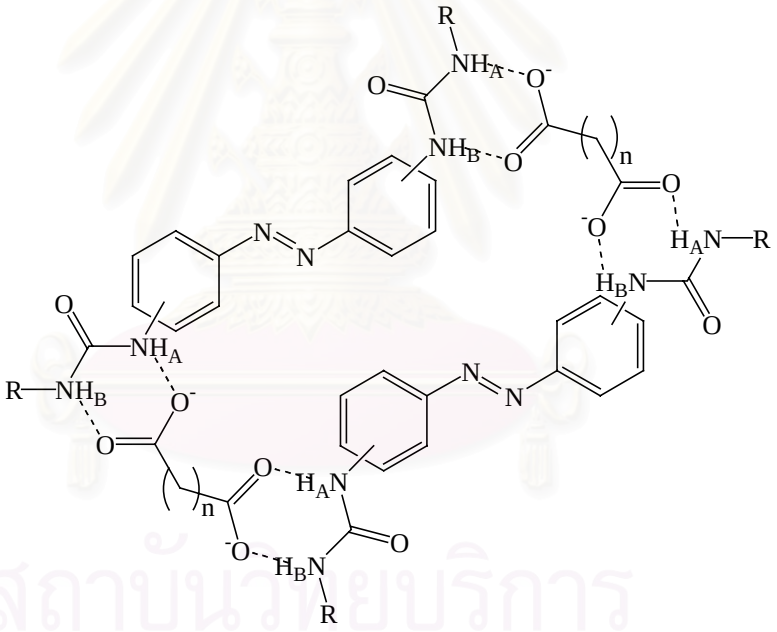
From Table 3.3 showed that K values falled into two ranges and ligand bind anion in a 1:1 fashion. Anions in the first range were oxalate, malonate and succinate. They were a group of shorter dicarboxylate. We forecast that shorter dicarboxylate anions will bind with ligands **2b** and **5a** in a molecular box pattern (Figure 3.11). This binding preferably formed with oxalate because it had the highest K value in this range.




**2b** *meta* ; R = hexyl

**5a** *para* ; R = butyl

**Figure 3.10** A possible structure for the complex between **2b** and **5a** with acetate.



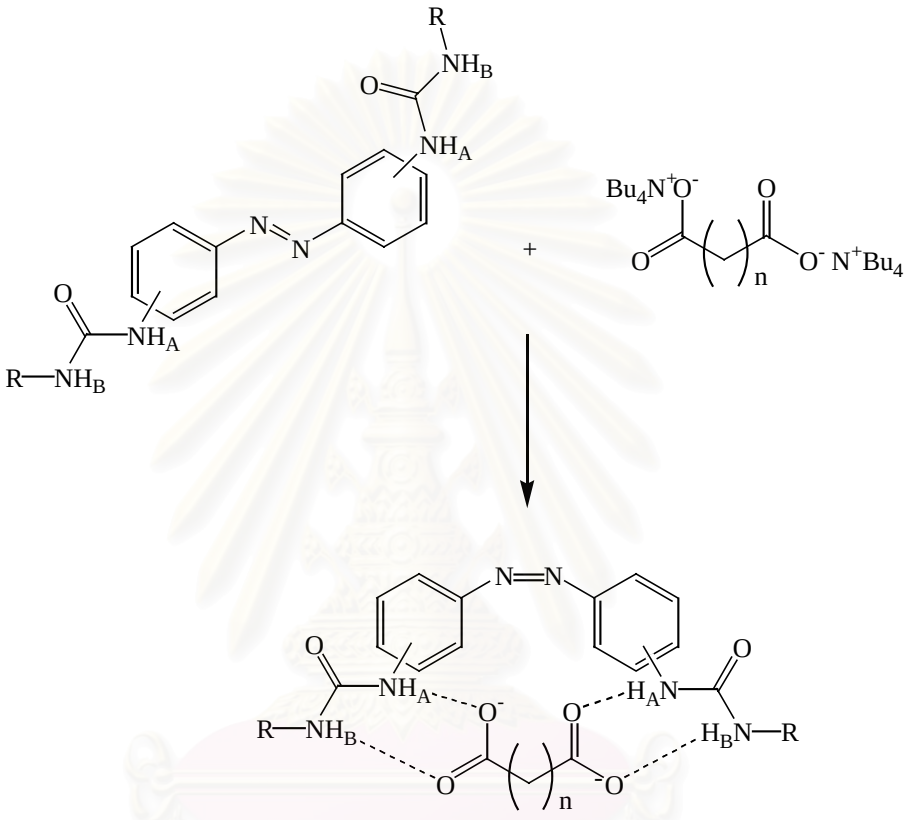

**2b** *meta* ; R = hexyl

**5a** *para* ; R = butyl

n = 0 (oxalate), 1 (malonate) and 2 (succinate)

**Figure 3.11** A possible structure for complexes between **2b** and **5a** with shorter dicarboxylate anions.

Other dicarboxylates, glutarate, adipate, pimelate, suberate and azelate, had chain lengths (n) longer than dicarboxylates in the first group. The cavity of azobenzene group in the *trans*-form was thus suitable for longer dicarboxylates using H-bond donors from both urea groups to bind with dicarboxylates (Figure 3.12). It was found that both **2b** and **5a** preferably bind suberate (with highest K values).




**Anion Complex**

**2b** *meta* ; R = hexyl

**5a** *para* ; R = butyl

n = 3 (glutarate), 4 (adipate), 5 (pimelate), 6 (suberate) and 7 (azelate)

**Figure 3.12 Compounds 2b and 5a and a possible structures of complex as between 2b and 5a with longer dicarboxylate anions.**

### 3.2.2 Complexation studies of compounds 2d and 5d with various dicarboxylate anions by UV-vis spectrophotometry

Figure 3.13 shows changes in absorption spectra of ligand **2d** (recorded in DMSO at a concentration of 2.5 x $10^{-5}$ M) observed upon addition of tetrabutylammonium suberate. In the absence of anions, the absorption spectrum of **2d** is characterized by the presence of one absorption maximum peak at 355 nm. Upon the addition of suberate anion, the peak at 355 nm decreased while two new peaks appeared at 400 and 480 nm. Complexation with other anions such as acetate, oxalate, malonate, succinate, glutarate, adipate, pimelate and azelate resulted in a similar trend.

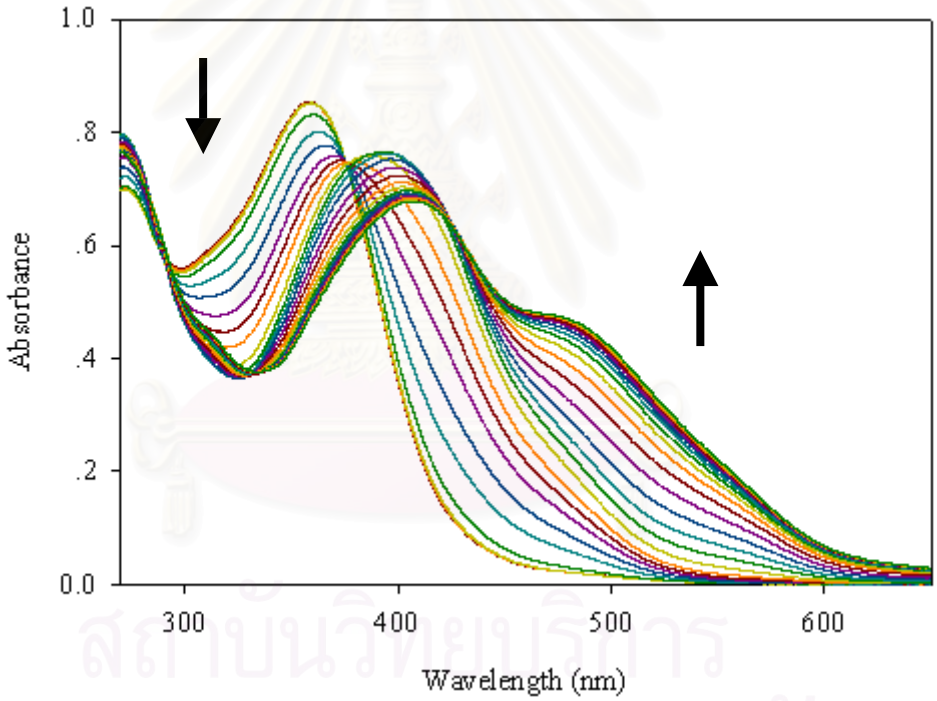



**Figure 3.13** UV-vis titration spectra of compound **2d** with suberate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [suberate] = 0-10 equiv.).

The UV-vis spectra of compound **2d** after addition of 10 equivalents of each anion are presented in Figure 3.14. Compound **2d** exhibited color change from light yellow to deep yellow upon addition of 10 equivalents of various dicarboxylate anions.

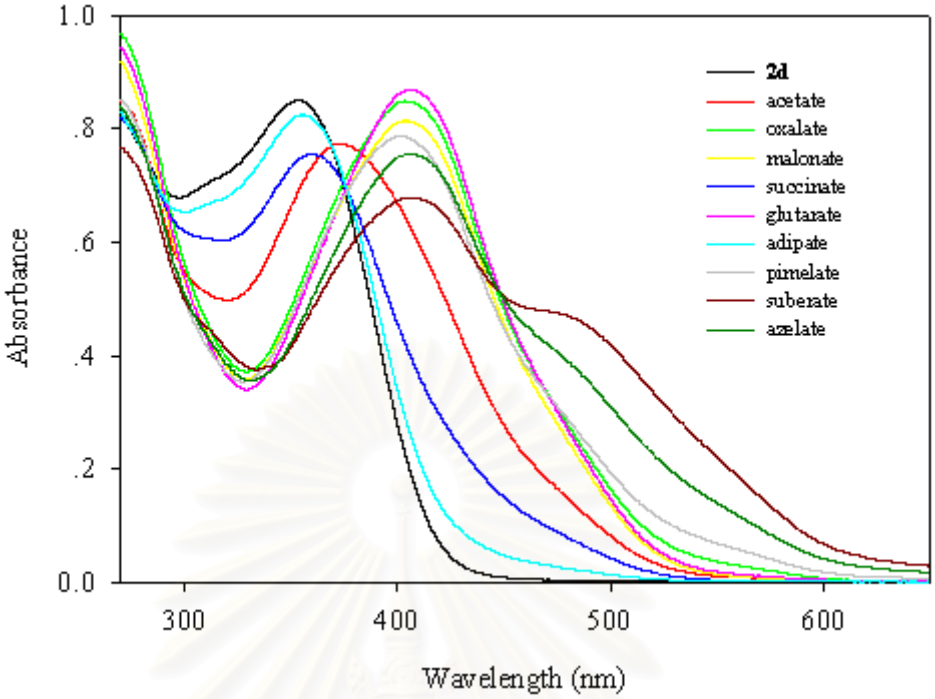



**Figure 3.14** UV-vis absorption spectra of **2d** recorded in DMSO (2.5 x $10^{-5}$ M) after the addition of 10 equivalents of dicarboxylate anions.

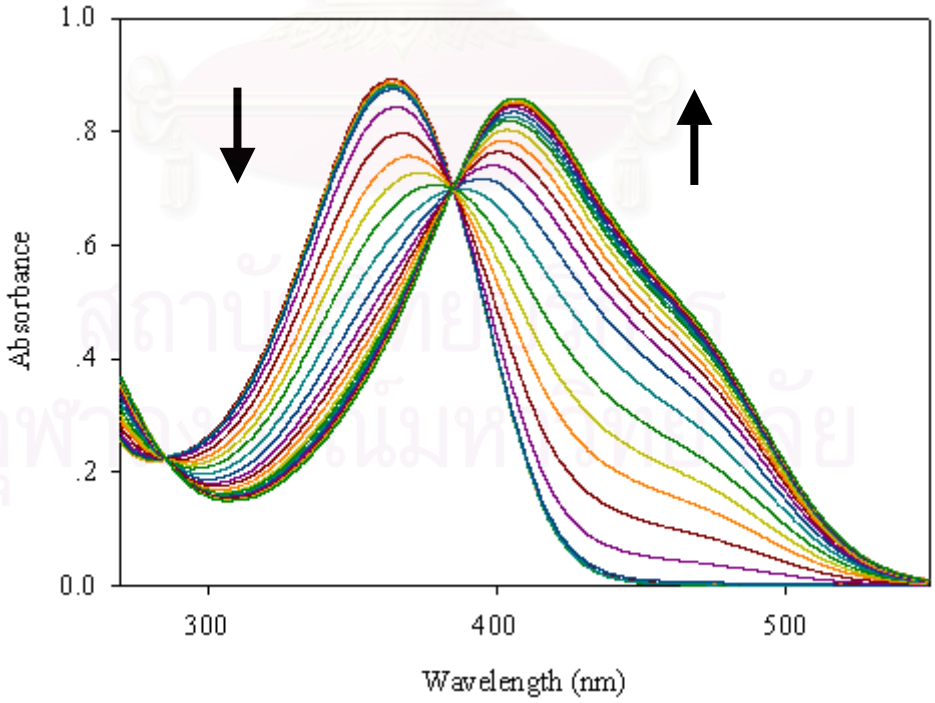



**Figure 3.15** UV-vis titration spectra of compound **5d** with suberate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [suberate] = 0-8 equiv.).

UV-vis spectra of **5d** in the absence of dicarboxylate anions, showed the absorption maxima at 364 nm. Figure 3.15 shows the dependence of UV-vis spectra of **5d** in DMSO on the equivalent of tetrabutylammonium suberate producing significant bathochromic shift in the $\lambda_{max}$ from 364 to 407 nm, concomitant with a solution color change from light yellow to red-pink. Isobestic points appear at 286 and 385 nm. Similar spectra were observed for the titration of **5d** with other anions (Figure 3.16).

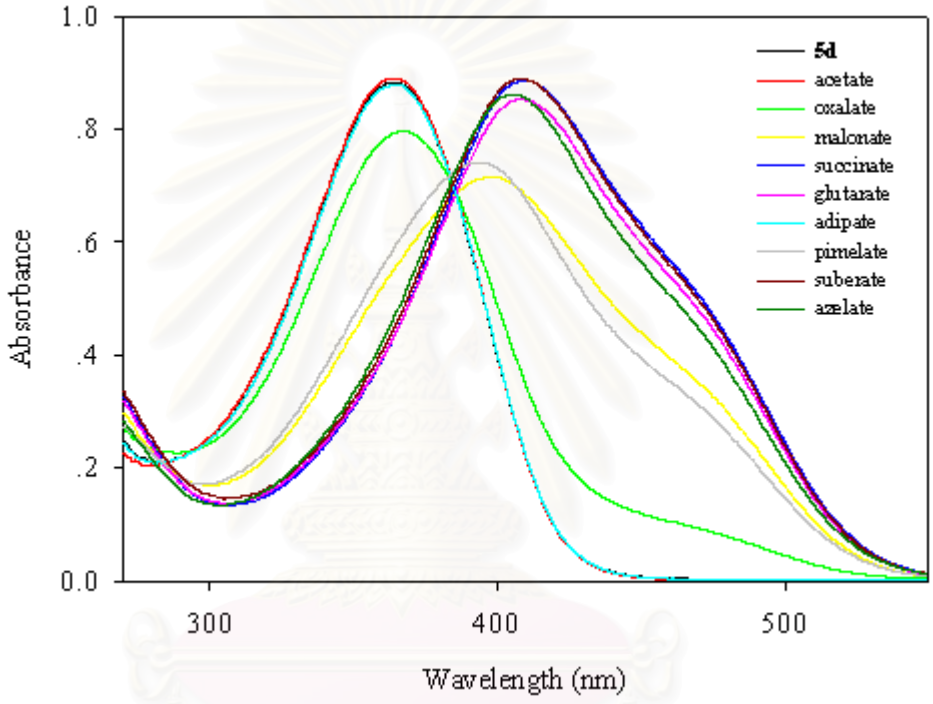



**Figure 3.16** UV-vis absorption spectra of **5d** recorded in DMSO ($1.5 \times 10^{-5}$ M) after the addition of 10 equivalents of dicarboxylate anions.

The UV-vis spectra of compound **5d** after addition of 10 equivalents of each anion are presented in Figure 3.16. Compound **5d** exhibited color change from light yellow to red-pink upon addition of 10 equivalents of various dicarboxylate anions.

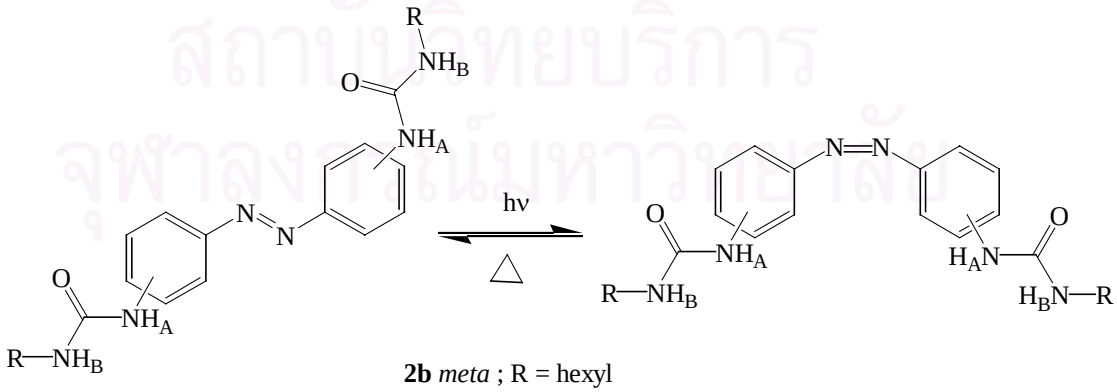
As can be expected from UV-vis data, a color change occurred by addition of dicarboxylate anions to the solution of **2d** and **5d**. More pronounced spectral changes for **2d** and **5d** were induced by addition of acetate, oxalate, malonate, succinate, glutarate, adipate, pimelate, suberate and azelate in DMSO (Figures 3.13 and 3.15). This may be due to the electronic excitation through charge transfer from the nitrogen

donor of the thiourea to an acceptor substituent (-$NO_2$) of the chromophore. The excited state would be more stabilized by anion binding, resulting in a bathochromic shift in the absorption maxima as well as color change.

Unfortunately, the binding constants of complexes between **2d** and **5d** and various dicarboxylate anions cannot be calculated from UV-vis titrations by Sirko program (version 1.0 beta).[45] In fact, the plots between the absorbance versus the equivalent of anions were similar to an acid-base titration curve. It is possible then that there might have been pH changes during the titrations which was actually found in a separate experiment. The abrupt change in absorbance in absorbance observed at 10 equivalents thus could be resulting from the deprotonation of the ligands (to dicarboxylate anions), considering the fact that guest species are basic and that ligands contain deprotonable groups.

### 3.2.3 Photoirradiation studies

Compounds **2b** and **5a** have azobenzene groups which can undergo conversion from *trans*- to *cis*-forms on irradiation with the UV light in solution. The ground state of compounds **2b** and **5a** is in the *trans*-form. On irradiation of compounds **2b** and **5a** with the UV light obtained from a medium pressure Hg lamp, the energetically preferred ground state *trans*-form changes to the *cis*-form *via* photochemical isomerisation process (Figure 3.17).




**2b** *meta* ; R = hexyl

**5a** *para* ; R = butyl

**Figure 3.17** The *trans-cis* isomerization of compounds **2b** and **5a**.

### 3.2.2.1 Complexation studies of compounds 2b and 5a with various dicarboxylate anions using $^1$H-NMR titrations

Solutions of compounds **2b** and **5a** were irradiated with 450 W medium pressure Hg lamp at room temperature for 15 minutes. The $^1$H-NMR spectra of compounds **2b** and **5a** were recorded. Although $^1$H-NMR spectra of compounds **2b** and **5a** both before and after irradiation have no change, the UV-vis spectra of **2b** and **5a** change dramatically. Two different N*H* signals were observed at 7.50 and 5.32 ppm for **2b** and at 7.69 and 5.39 ppm for **5a**. As shown in Tables 3.4 and 3.5, all the NH protons of compounds **2b** and **5a** showed significant downfield shift upon addition of guest anions, indicating that all four NH protons participate in the complexation with anions. For example, all the NH signals in $^1$H-NMR spectra of titration between **2b** and **5a** with suberate shifted downfield as shown in Figures 3.18 and 3.19.

**Table 3.4** $^1$H-NMR chemical shifts (ppm) for compound **2b** (after irradiation) in the absence and presence of dicarboxylate anions.

| Anions | $H_A$ | $H_B$ |
|---|---|---|
| None | 7.50 | 5.32 |
| Acetate | 11.04 | 8.22 |
| Oxalate | 11.87 | 9.20 |
| Malonate | 11.77 | 9.18 |
| Succinate | 12.25 | 9.55 |
| Glutarate | 11.96 | 9.33 |
| Adipate | 11.35 | 8.17 |
| Pimelate | 11.90 | 9.20 |
| Suberate | 12.05 | 9.36 |
| Azelate | 11.92 | 9.20 |

**Table 3.5** $^{1}$H-NMR chemical shifts (ppm) for compound **5a** (after irradiation) in the absence and presence of dicarboxylate anions.

| Anions | $H_A$ | $H_B$ |
|---|---|---|
| None | 7.70 | 5.42 |
| Acetate | 11.56 | 8.61 |
| Oxalate | 11.96 | 9.31 |
| Malonate | [a] | 9.57 |
| Succinate | 10.99 | 7.63 |
| Glutarate | 12.54 | 9.77 |
| Adipate | 10.99 | 7.59 |
| Pimelate | 12.24 | 9.41 |
| Suberate | 12.56 | 9.74 |
| Azelate | 12.53 | 9.71 |

[a] N$H_A$ signal could not be observed.

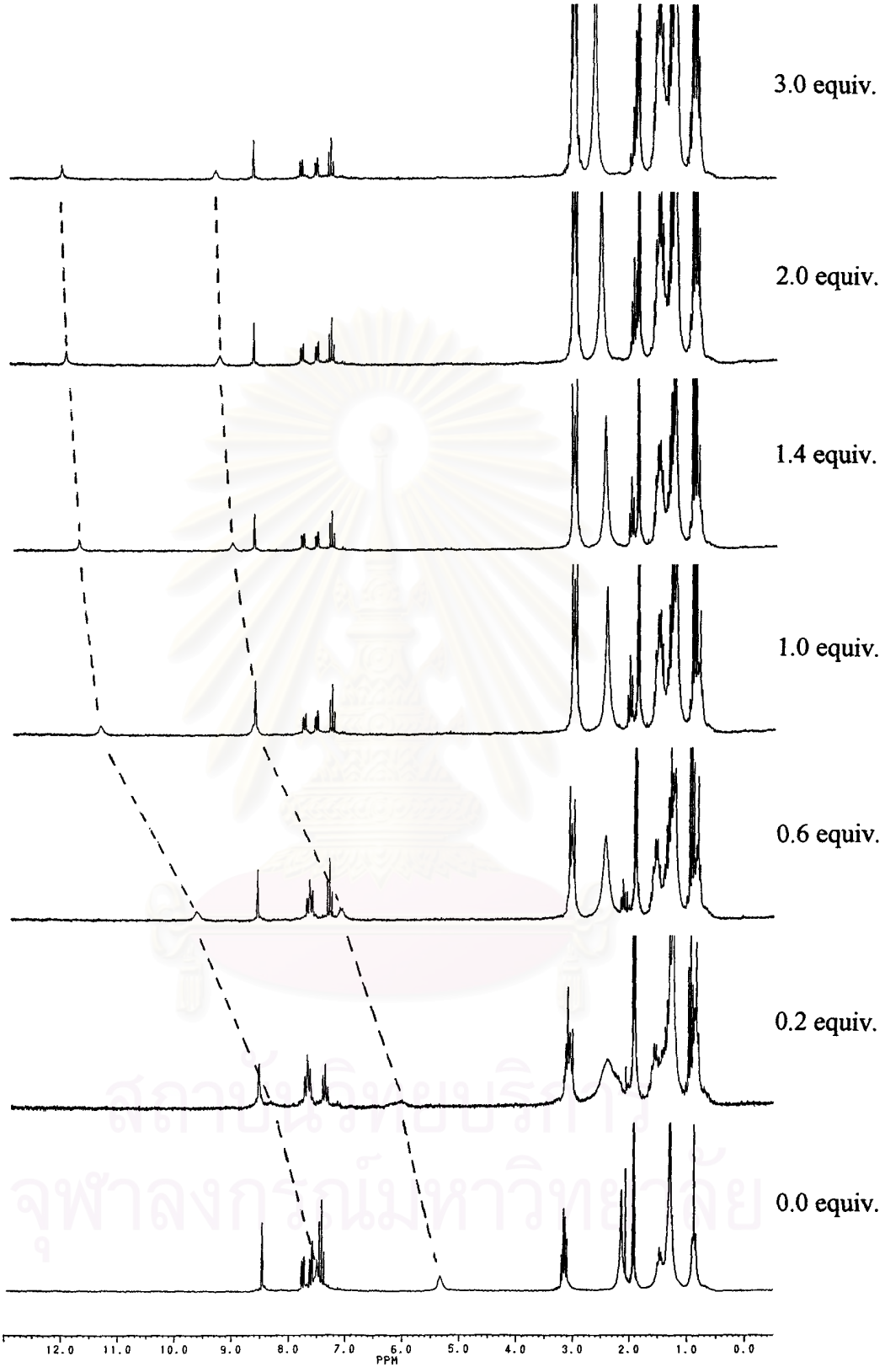



**Figure 3.18** $^{1}$H-NMR spectra of **2b** (after irradiation) and suberate in $CD_3CN$ with 200 MHz.

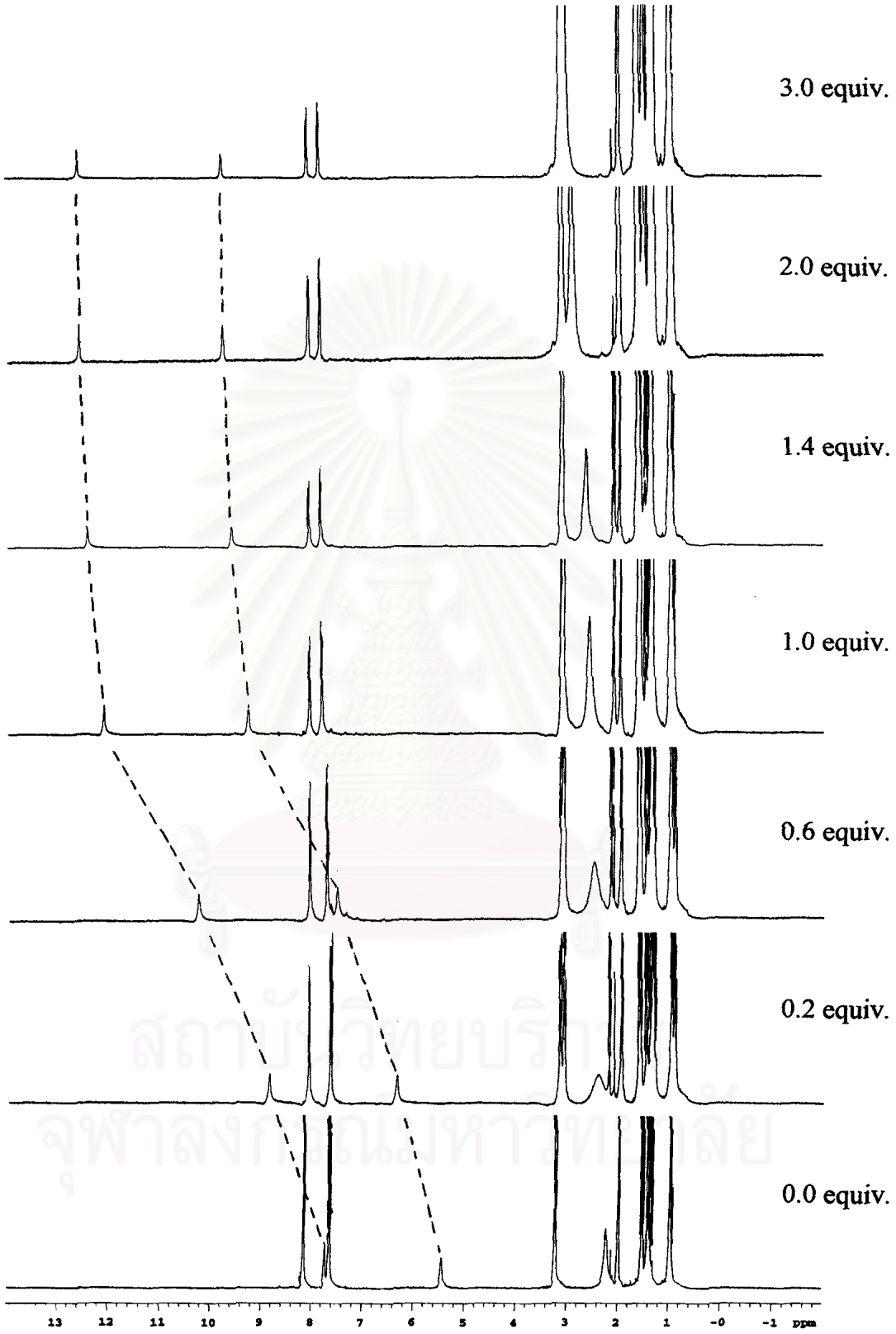



**Figure 3.19** $^{1}$H-NMR spectra of **5a** (after irradiation) and suberate in $CD_3CN$ with 400 MHz.

Plots between $^{1}$H chemical shift of N$H_A$(CO)N$H_B$ and equivalents of dicarboxylate anions for ligands **2b** and **5a** are displayed in Figures 3.20 and 3.21. The plots suggest that ligands **2b** and **5a** form complexes with dicarboxylate anions in a 1:1 fashion which is consistent with Job's plots (Figures 3.22 and 3.23).

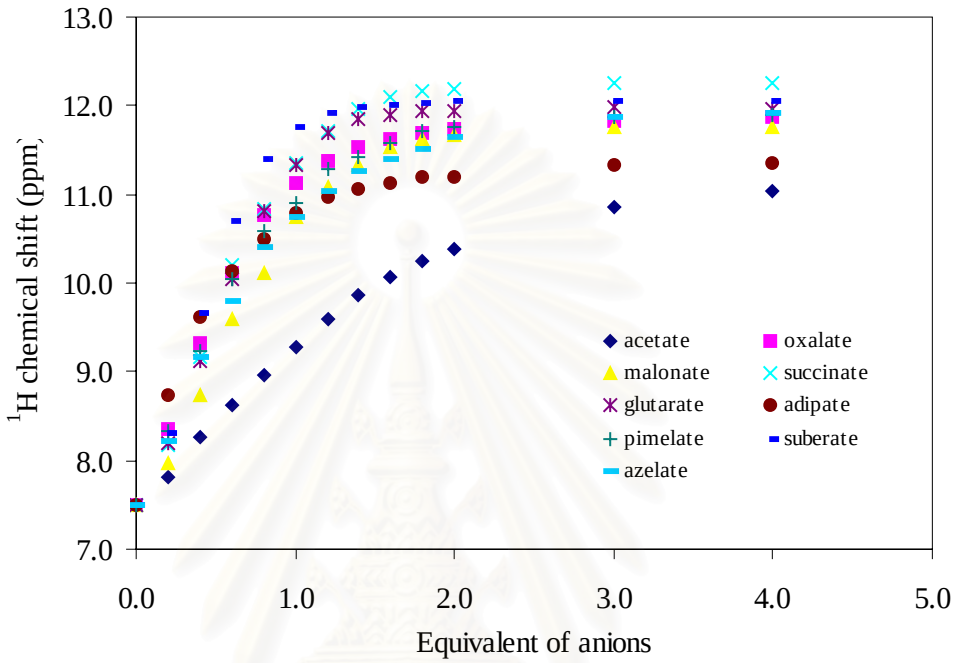



**Figure 3.20** Titration curves between **2b** after irradiation (N$H_A$) with various dicarboxylate anions in $CD_3CN$.

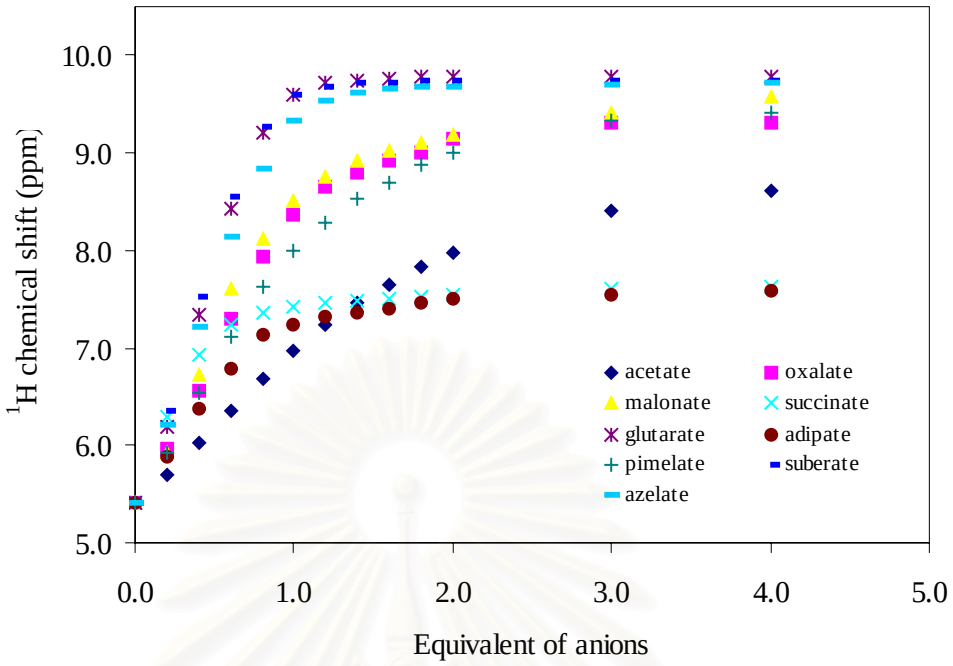



**Figure 3.21** Titration curves between **5a** after irradiation (N$H_B$) with various dicarboxylate anions in $CD_3CN$.

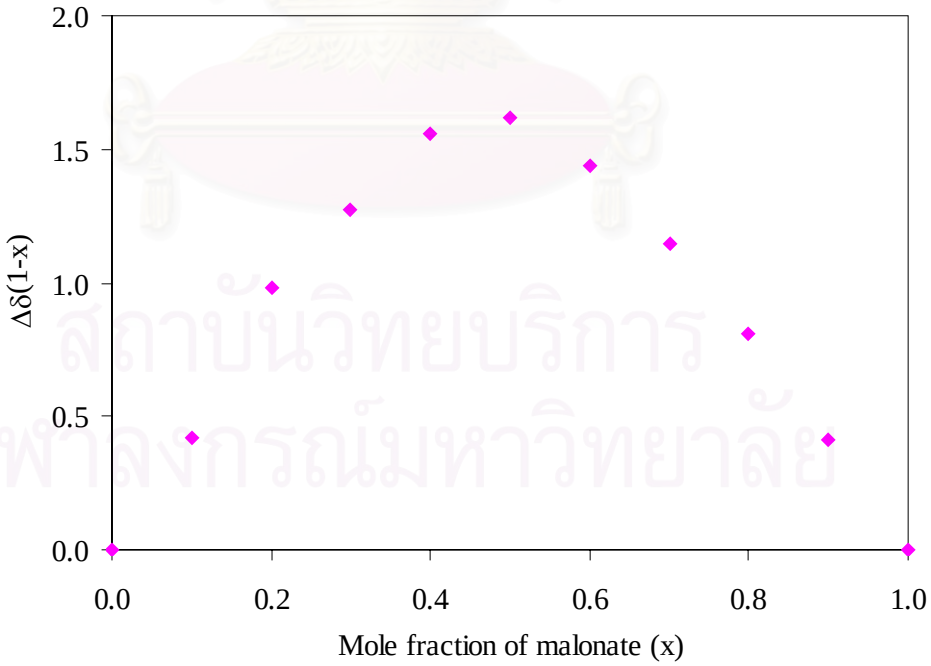



**Figure 3.22** The Job's plot of compound **2b** after irradiation (N$H_A$) with malonate.

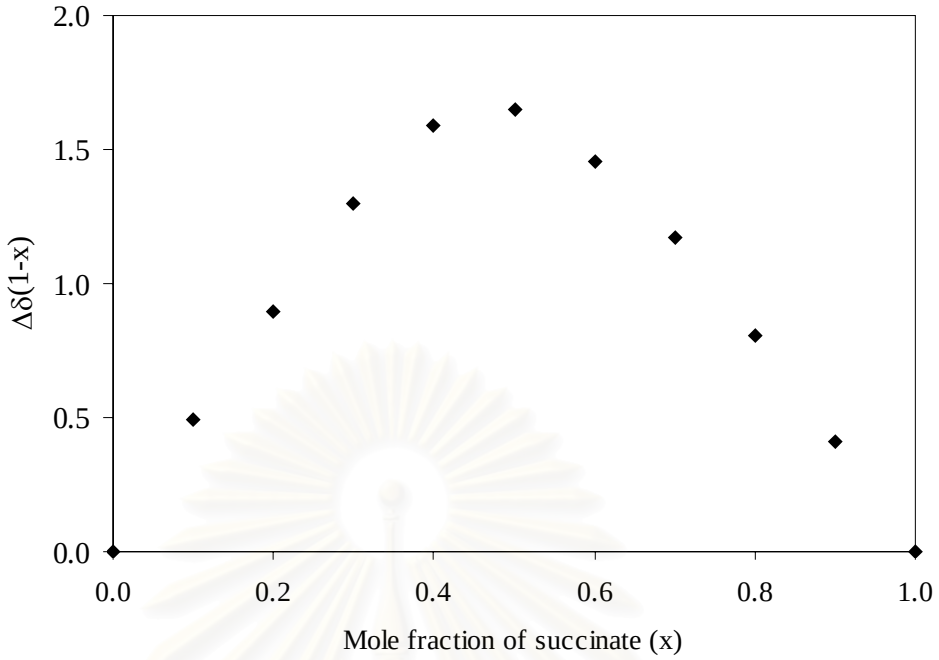



**Figure 3.23** The Job's plot of compound **5a** after irradiation (N$H_B$) with succinate.

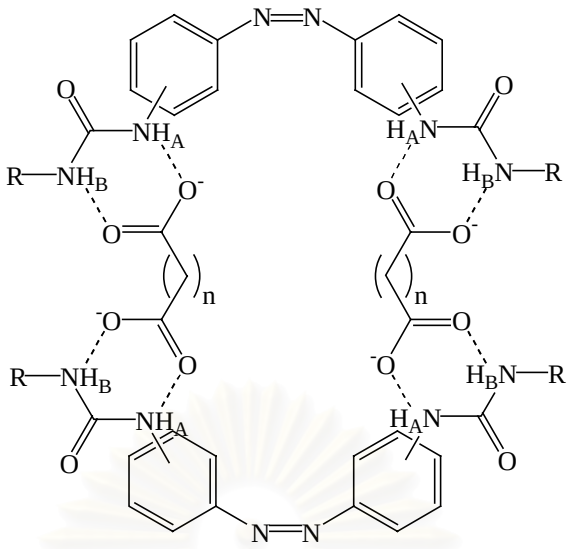
The association constants calculated from the changes in chemical shifts of the N$H_A$ and N$H_B$ hydrogens using the EQNMR program[44] are summarized in Table 3.6. The signal for the N$H_A$ hydrogen of compound **5a** became broad upon the addition of malonate anion. Thus, the association constant of compound **5a** towards malonate can be calculated from changes in chemical shifts of the N$H_B$ hydrogen.

**Table 3.6** Binding constants of compounds **2b** and **5a** (after irradiation) toward various dicarboxylate anions.

| Anions | Compound **2b** | Compound **5a** |
|---|---|---|
| Acetate | 138 | 158 |
| Oxalate | 2752 | 1793 |
| Malonate | 1321 | 1172[c] |
| Succinate | 2413 | 6709 |
| Glutarate | 5104 | 26107 |
| Adipate | 2245 | 4319 |
| Pimelate | 1400 | 744 |
| Suberate | 28731 | 35193 |
| Azelate | 855 | 14861 |

[c] Calculate from the change in chemical shift of N$H_B$.

From Table 3.6 showed that K values falled into two ranges. The first range was acetate, oxalate, malonate, succinate, glutarate and adipate. They were a group of shorter dicarboxylates. We suspect that shorter dicarboxylate anions will bind with ligands **2b** and **5a** in a molecular box pattern (Figure 3.24) in their *cis*-forms. Both ligands **2b** and **5a** preferably bind glutarate.



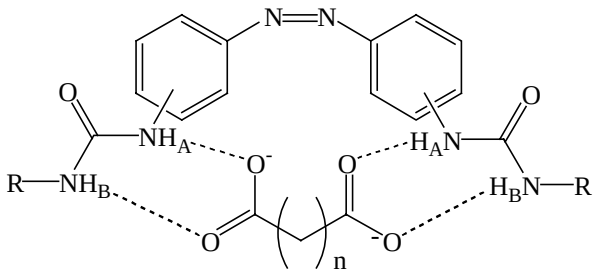
**2b** *meta* ; R = hexyl

**5a** *para* ; R = butyl

n = 0 (oxalate), 1 (malonate), 2 (succinate), 3 (glutarate) and 4 (adipate)

**Figure 3.24 A possible structure for the complex between 2b and 5a (after irradiation) with shorter dicarboxylate anions.**

Other longer dicarboxylates, pimelate, suberate and azelate, had chain length (n) longer than the first group. The *cis*-form of receptors **2b** and **5a** after irradiation, were locked in the presence of longer dicarboxylate anions by the formation of hydrogen bonds as shown in Figure 3.25. Formation of this 1:1 complex brought an additional stabilization of *cis*-configuration over the *trans*-form of receptors **2b** and **5a** and the extent of stabilization was strongly dependent on the formation of a tight complex which, in turn, was attributed to the matching of the chain length of dicarboxylate with the cavity size of the *cis*-form of receptors **2b** and **5a**. Here the cavity of the *cis*-form of the receptors **2b** and **5a**, where two thiourea binding motifs were flanked by photochemical switching azobenzene unit, were found to be specific for suberate. Moreover, the association constants of receptors **2b** and **5a** (after irradiation) toward suberate were about 10 times for **2b** and 30 times for **5a** as large as receptors **2b** and **5a** before irradiation (*trans* form), respectively.



**2b** *meta* ; R = hexyl

**5a** *para* ; R = butyl

n = 5 (pimelate), 6 (suberate) and 7 (azelate)

**Figure 3.25 A possible structure for the complex between 2b and 5a (after irradiation) with longer dicarboxylate anions.**

### 3.2.2.2 Complexation studies of compounds 2d and 5d with various dicarboxylate anions using UV-vis titrations

Compound **2d** in DMSO ($3.0 \times 10^{-5}$ M) exhibited a $\pi$-$\pi^*$ peak at 355 nm, and intensity of this peak decrease upon irradiation with light of 310-390 nm (Figure 3.26). The result indicated that **2d** can be isomerized from the *trans* to the *cis* form. The absorption spectrum of compound **2d** (after irradiation) showed two absorption bands at 313 and 377 nm. For example, upon the addition of tetrabutylammonium suberate to DMSO solution of **2d** (after irradiation), two bands at $\lambda_{max}$ = 313 and 377 nm decreased in intensity and a new intense band at $\lambda_{max}$ = 511 nm emerged (Figure 3.27).

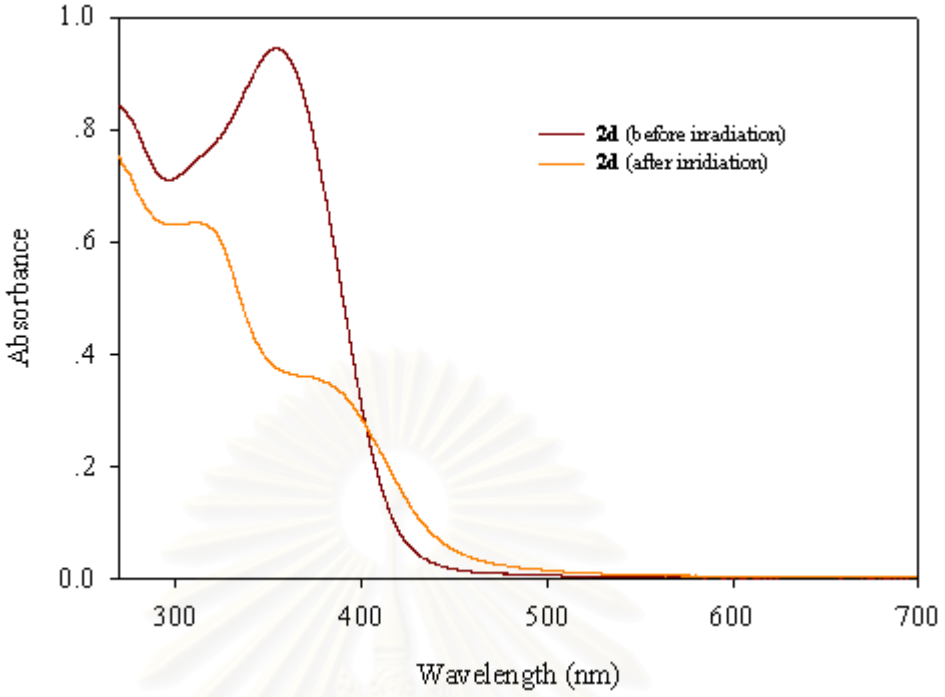



**Figure 3.26** UV-vis spectra of compound **2d** both before and after irradiation.

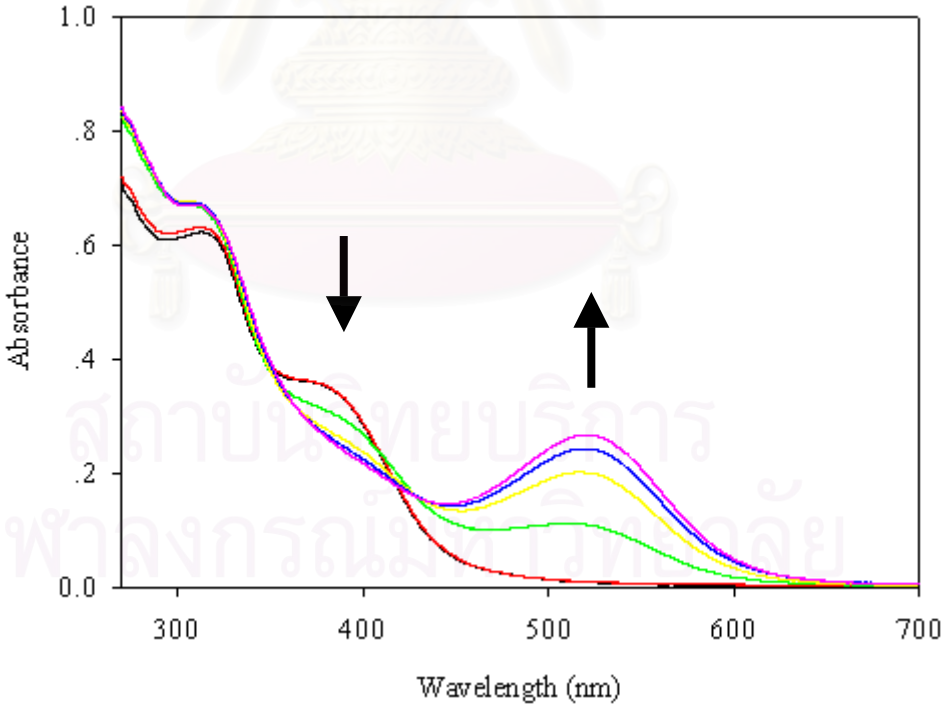



**Figure 3.27** UV-vis titration spectra of compound **2d** (after irradiation) with suberate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [suberate] = 0-25 equiv.).

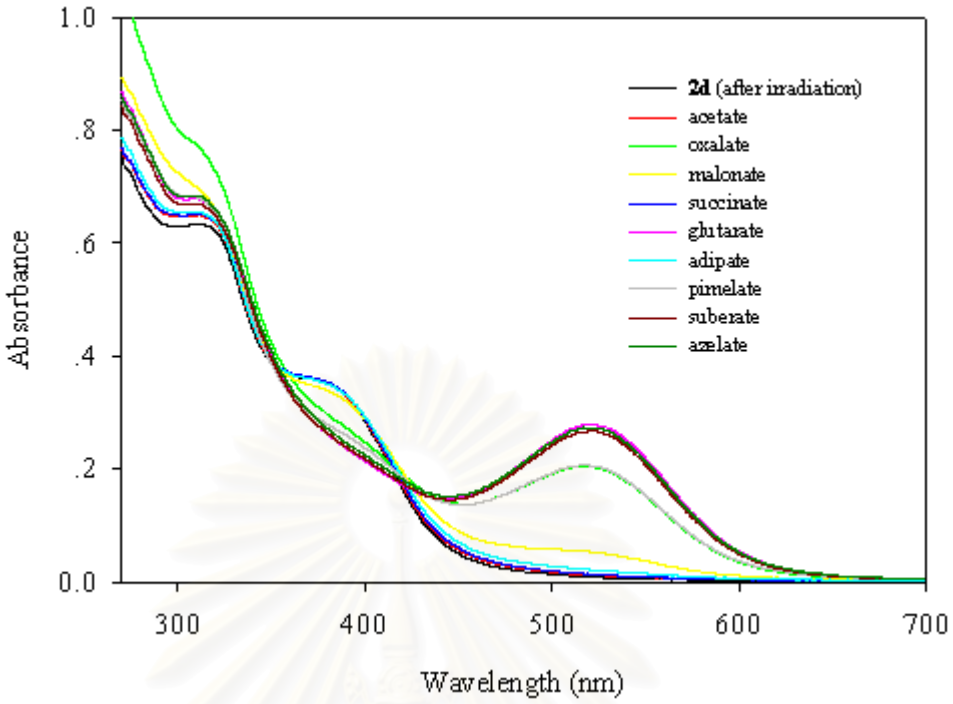



**Figure 3.28** UV-vis absorption spectra of **2d** recorded in DMSO ($3.0 \times 10^{-5}$ M) after the addition of 20 equivalents of dicarboxylate anions.

As expected from UV-vis data, color change occurs by addition of dicarboxylate anions to the solution of **2d** after irradiation (Figure 3.28). With addition of 20 equivalents of each anion, the color of the solution changed from light yellow to red-pink. It is thus as possible to use **2d** as dicarboxylate anion sensor by spectrophotometry.

Figure 3.29 shows the absorbance spectra of compound **5d** obtained by UV-photoirradiation and non-photoirradiation of **5d**.The absorption spectrum of **5d** in DMSO ($3.0 \times 10^{-5}$ M) shows a strong band at 364 nm. After UV-photoirradiation, the absorption spectrum of **5d** at 260-300 and 460-500 nm was increased and at 320-410 nm was decreased, which indicated *trans* to *cis* isomerization.

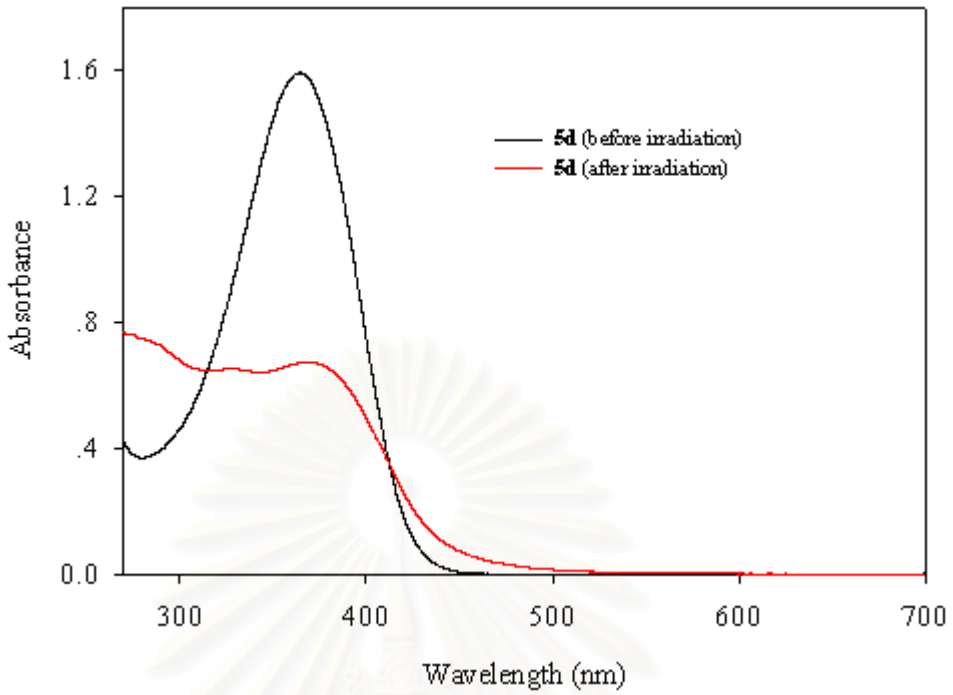



**Figure 3.29** UV-vis spectra of compound **5d** both before and after irradiation.

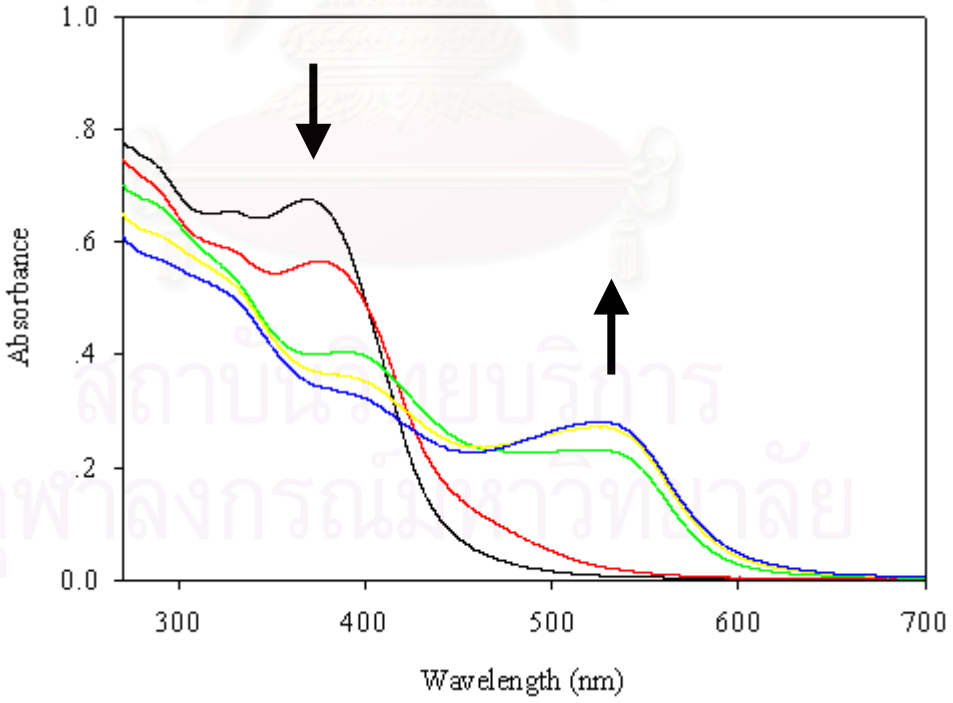



**Figure 3.30** UV-vis titration spectra of compound **5d** (after irradiation) with suberate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [suberate] = 0-20 equiv.).

In the absence of dicarboxylate anions, the absorption spectrum of compound **5d** (after UV-irradiation) shows one absorption maximum peaks at 368 nm. Figure 3.30 shows the changes in the absorption spectrum of **5d** (after UV-irradiation) observed upon the addition of tetrabutylammonium suberate, the peak at 368 nm decreased while a new peak appears at 530 nm concomitant with color change from light yellow to orange. This may be due to the electronic excitation through charge transfer from the nitrogen donor of the thiourea to an acceptor substituent ($-NO_2$) of the chromophore. The excited state would be more stabilized by anion binding, resulting in a bathochromic shift in the absorption maxima as well as color change. Similar spectra were observed for the titration of **5d** with other anions.

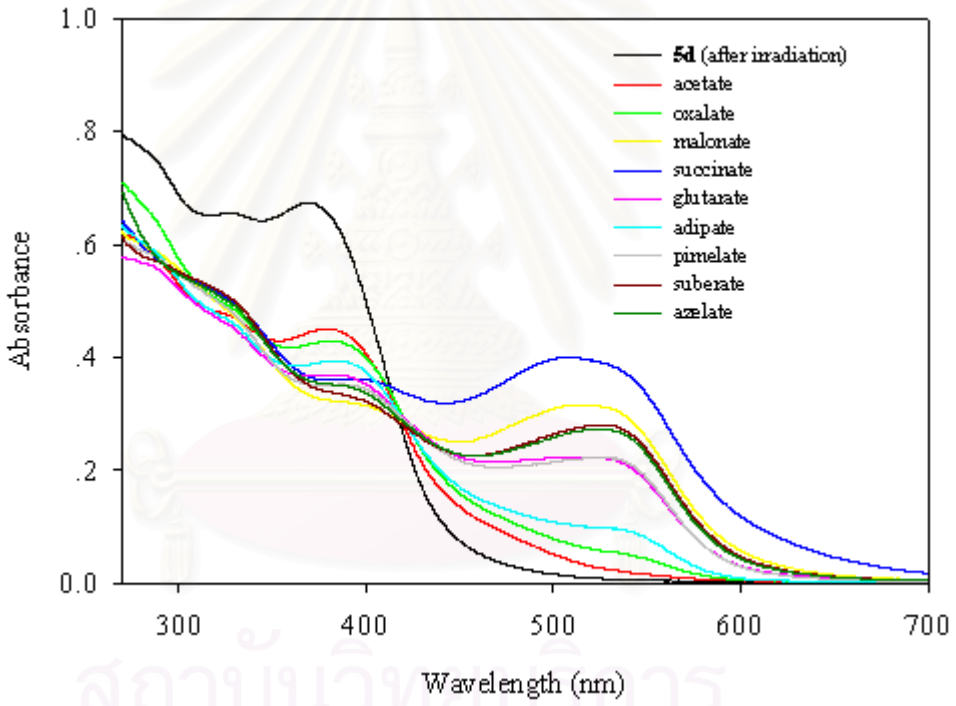



**Figure 3.31** UV-vis absorption spectra of **5d** recorded in DMSO ($3.0 \times 10^{-5}$ M) after the addition of 20 equivalents of dicarboxylate anions.

As expected from UV-vis data, a color change occurs through addition of dicarboxylate anions to the solution of **5d** after irradiation (Figure 3.31).Upon the addition of 20 equivalents of each anion, the color of the solution changed from light yellow to orange. It is thus possible to use **5d** as dicarboxylate anion sensor by spectrophotometry.

Unfortunately, the binding constants of complexes between **2d** and **5d** and various dicarboxylate anions cannot be calculated from UV-vis titrations by Sirko program (version 1.0 beta).[45] In fact, the plots between the absorbance versus the equivalent of anions were similar to an acid-base titration curve. It is possible then that there might have been pH changes during the titrations which was actually found in a separate experiment. The abrupt change in absorbance in absorbance observed at 10 equivalents thus could be resulting from the deprotonation of the ligands (to dicarboxylate anions), considering the fact that guest species are basic and that ligands contain deprotonable groups.

# CHAPTER IV

# CONCLUSION

Azobenzene derivatives containing urea or thiourea groups, **2a**, **2b**, **2c**, **2d**, **5a**, **5b**, **5c** and **5d**, have been synthesized in two steps. Reductive couplings of nitro groups on *m*- and *p*-nitroaniline gave **1** (61%) and **3** (36%), respectively. Coupling reactions between **1** and **3** with *n*-butylisocyanate, hexylisocyanate, phenylisocyanate and *p*-nitrophenyl isothiocyanate yielded **2a** (77%), **2b** (92%), **2c** (62%), **2d** (56%) and **5a** (79%), **5b** (87%), **5c** (62%), **5d** (57%), respectively.

$^{1}$H-NMR titrations showed that ligands **2b** and **5a** were able to form complexes with dicarboxylate anions. It was found that acetate anion can form complexes with the ligands in 2:1 ratios. Both shorter and longer dicarboxylate anions showed 1:1 complexation. Stoichiometry of anions and association constants were found to be strongly dependent on the chain length of dicarboxylate anions and distance between the urea units. Shorter dicarboxylate anions (n = 0-2) will bind ligands **2b** and **5a** in a molecular box pattern. Both **2b** and **5a** formed the most stable complexes with oxalate. Longer dicarboxylate anions (n = 3-7) can bind **2b** and **5a** in their *trans* form. Both **2b** and **5a** formed the most stable complexes with suberate.

Upon photoirradiation of ligands **2b** and **5a**, acetate and dicarboxylate anions formed complexes with the ligands in a 1:1 stoichiometry in all cases. After irradiation, association constants of the *cis*-form of ligands **2b** and **5a** and suberate are about 10-30 times larger than those of ligands **2b** and **5a** before irradiation. However, the *cis*-form of **5a** can form more stable complexes with suberate than the *cis*-form of **2b**. The results suggests that *cis*-form of **5a** has a suitable cavity size for binding suberate

UV-vis titrations showed that new bands gradually appeared and moved to longer wavelengths upon addition of dicarboxylate anions while the characteristic peaks at 355 nm for **2d** and 364 nm for **5d** decreased. New bands indicated that

ligands **2d** and **5d** were able to form complexes with dicarboxylate anions *via* hydrogen-bonding interactions and gave a color change which can be detected by the naked eyes. On irradiation of ligands **2d** and **5d**, absorption spectra of characteristic peaks of **2d** at 355 nm and **5d** at 364 nm were decreased and new bands appeared at longer wavelengths (450-500 nm), signifying *trans*- to *cis*- isomerization. Upon addition of dicarboxylate anions, new bands appeared at 511 nm for **2d** and 530 nm for **5d** concomitant with a color change of the solution. This may be due to the electronic excitation through charge transfer from the nitrogen donor of the thiourea to an acceptor substituent ($-NO_2$) of the chromophore. The excited state would be more stabilized by anion binding, resulting in a bathochromic shift in the absorption maxima as well as a color change. The complexation properties of **2d** and **5d** suggest that both of them can be potentially used as dicarboxylate anion sensors.

**Suggestions for future work:**

Future works should be focused on:

1. X-ray crystal structures of ligands **2b** and **5a** and their dicarboxylate anion complexes should be obtained in order to understand structures of synthetic receptors and their coordination chemistry with dicarboxylates anions.
2. Synthesize other derivatives of azobenzene containing urea or thiourea such as *o*-urea or *o*-thiourea to compare and study their complexation and photoirradiation.

## REFERENCES


1. P. D. Beer and P. A. Gale. “Anion recognition and sensing: the state of the art and future perspectives”, *Angew. Chem. Int. Ed.* **2001**, 40, 486.
2. P. D. Beer. “Transition-metal receptor system for the selective recognition and sensing of anionic guest species”, *Acc. Chem. Res.* **1998**, 31, 71.
3. B. J. Calnan, B. Tidor, S. Biancalana, D. Hudson and A. D. Frankel. “Arginine-mediated RNA recognition: the arginine fork”, *Science.* **1991,** 252, 1167.
4. Bianchi, A., Bowman-James, K., Garcia-Espana, E., Eds.; “*Supramolecular chemistry of Anion*”, Wiley-VCH, New York, **1997**, p.148.
5. J. Scheerder, S. F. S. Engbersen and D. N. Reinhoudt. “Synthetic receptors for anion complexation”, *Recueil des Travaux Chimiques des Pays-Bas.* **1996**, 115, 307.
6. J. L. Sessler, A. Andrievsky, V. Kral and V. Lynch. “Chiral recognition of dicarboxylate anions by sapphyrin-based receptors”, *J. Am. Chem. Soc.* **1997**, 119, 19385.
7. J. M. Benito, M. Gomez-Garcia, J. L. J. Blanco, C. O. Mellet and J. M. Gfernandez “Carbohydrate-based receptors with multiple thiourea binding sites. Multipoint hydrogen bond recognition of dicarboxylates and monosacharides”, *J. Org. Chem.* **2001**, 66, 1366.
8. S. Sasaki, M. Mizuno, K. Neamura and Y. Tobe “Synthesis and anion-selective complexation of cyclophen-based cyclic thioureas”, *J. Org. Chem.*, **2000**, 65, 275.
9. T. S. Snowden and E. V. Anslyn, “Anion recognition: Synthetic receptors for anions and their application in sensors”, *Current. Opinion in Chemical Biology.* **1999**, 3, 740
10. P. D. Beer. “Anion selective recognition and optical/electrochemical sensing by novel transition metal receptor systems”, *Chem. Commun.* **1996**, 689.
11. C. Suksai and T. Tuntulani. “Chromogenic anion sensors”, *Chem. Soc. Rev.* **2003**, 32, 192.
12. P. A. Gale. “Anion coordination and anion-directed assembly: highlights from 1997 and 1998”, *Coor. Chem. Rev.* **2000**, 199, 181.

13. P. J. Smith, M. V. Reddington and C. S. Wilcox. “Ion pair binding by a urea in chloroform solution”, *Tetrahedron Lett.* **1992**, 33, 6085.

14. S . Valiyaveettil, J. F. J. Engberson, W. Verboom and D. N. Reinhoudt. “Synthesis and complexation studies of neutral anion receptors”, *Angew. Chem., Int. Ed. Engl.* **1993**, 32, 900.

15. P. Buhlmann, S. Nishizawa, K. P. Xiao and Y. Umezawa. “Strong hydrogen bond-mediated complexation of $H_2PO_4^-$ by neutral bis-thiourea hosts”, *Tetrahedron.* **1997**, 53, 1647.

16. H. Miyaji and J. L. Sessler. “ Off-the-shelf colorimetric anion sensors”, *Angew. Chem. Int. Ed.* **2001**, 40, 154.

17. A. P. deSilver, H. Q. N. Gunaratne, T. Gunnlaugsson. A. J. M. Huxley, C. P. McCoy, J. T. Rademacher and T. E. Rice. “Signaling recognition events with fluorescent sensors and switches”, *Chem. Rev.* **1997**, 97, 1515.

18. L. Fabbrizzi and A. Poggi. “Sensors and switches from supramolecular chemistry”, *Chem. Soc. Rev.* **1995**, 24, 197.

19. K. Koumoto, M. Takeuchi and S. Shinkai. “Design of a visualized sugar sensing system utilizing a boronic acid azopyridine interaction”, *Supramol. Chem.* **1998**, 9, 203.

20. P. A. Gale, L. J. Twyman, C. I. Handlin and J. L. Sessler. “A colourimetric calix[4]pyrrole-4-nitrophenolate based anion sensor”, *Chem. Commum.* **1999**, 1851.

21. J. O. Smith, D. A. Olson and B. A. Armitage. “Molecular recognition of PNA-containing hybrids: spontaneous assembly of helical cyanine dye aggregates on PNA templates”, *J. Am. Chem. Soc.* **1999**, 121, 1686.

22. G. Hennrich, H. Sonnenschein and U. Resch-Genger. “Fluorescent anion receptors with iminoylthiourea binding sites-selective hydrogen bond meiated recognition of $CO_3^{2-}$, $HCO_3^-$ and $HPO_4^{2-}$”, *Tetrahedron Lett.* **2001**, 42, 795.

23. Y. Kubo, M. Tsukahara, S. Ishihara and S. Tokita. “A simple anion chemosensor based on a naphthalene-thiouronium dyad”, *Chem. Commun.* **2000**, 653.

24. J. Raker and T. E. Glass. “Selective via cooperative interaction: Detection of dicarboxylates in water by a pinwheel chemosensor”, *J. Org. Chem.* **2002**, 17, 6113.

25. L. Fabbrizzi, M. Licchelli, G. Rabaioli and A. Taglietti. “The design of luminescent sensors for anions and ionisable analytes”, *Coor. Chem. Rev.* **2000**, 85, 205.

26. S. Valiyaveettil, J. F. J. Engberson, W. Verboom and D. N. Reinhoudt. “Synthesis and complexation studies of neutral anion receptors”, *Angew. Chem. Int. Ed. Engl.* **1993**, 32, 900.

27. T. R. Kelly and M. H. Kim. “Relative binding affinity of carboxylate and its isosteres: nitro, phosphate, phosphonate, sulfonate and δ–lactone”, *J. Am. Chem. Soc.* **1994**, 116, 7072.

28. M. Mei and S. Wu. “Fluorescent sensor for α,ω-dicarboxylate anion”, *New J. Chem.* **2001**, 25, 471.

29. D. H. Lee, H. Y. Lee, K. H. Lee and Jong-In Hong. “Selective anion sensing based on a dual-chromophore approach”, *Chem. Commun*. **2001**, 1188.

30. D. H. Lee, H. Y. Lee and J. Hong. “Anion sensor based on the indoaniline-thiourea system”, *Tetrahedron Lett.* **2002**, 43, 7273.

31. F. Vogtle. *Supramolecular chemistry*; John Wiley & Sons: New York, **1993**, p.207.

32. N. J. Turro, *Molecular photochemistry*; W. A. Benjamin: New York, **1965**, p.199.

33. V. Balzani, F. Scandola. “*Supramolecular photochemistry*”; Ellis Horwood, New York, **1991**, p.197.

34. Neckers, D. C. “Photochemistry of azobenzene-containing polymers”, *Chem. Rev.* **1989**, 89, 1915.

35. H. Rau and E. Luddecke. “On the rotation-inversion controversy on photoisomerization of azobenzene. Experimental proof of inversion”, *J. Am. Chem. Soc.* **1982**, 104, 1616.

36. S. Shinkai, T. Minami, Y. Kusano and O. Manabe. “Photoresponsive crown ethers. 8. Azobenzene-type “switched-on” crown ethers which exhibit an all-or-nothing change in ion-binding ability”, *J. Am. Chem. Soc.* **1983**, 105, 1851.

37. S. Shinkai, T. Nakaji, Y. Nishida, T. Ogawa and O. Manabee. “Photoresponsive crown ethers. 1. cis-trans isomerism of azobenzene as a tool to enforce conformation changes of crown ethers and polymers”, *J. Am. Chem. Soc.* **1980**, 102, 5860.

38. S. Shinkai, T. Ogawa, Y. Kusano, O. Manabe, K. Kikukawa, T. Goto and T. Matsuda. “Photoresponsive crown ethers. 4. influence of alkali metal cation on photoisomerization and thermal isomerization of azobis(benzocrown ether)s”, *J. Am. Chem. Soc.* **1982**, 104, 1960.

39. L. Stryer. “*Biochemistry*”, 4th ed., W. H. Freeman, New York, **2000**, p.509.

40. H. Fenniri, M. W. Hosseini and J. M. Lenh. “Molecular recognition of NADP(H) and ATP by macrocyclic polyamines bearing acridine groups”, *Helv. Chim. Acta.* **1997**, 80, 786.

41. R. S. Furniss, A. J. Hannaford, P. W. G. Smith and A. R. Tatchell. “*Vogel’s textbook practical organic chemistry*”, 5th ed., John Wiley & Son, New York, **1989**, p. 957.

42. E. Dyer and T. B. Johnson. “Nitro and amino triphenylguanidines”, *J. Am. Chem. Soc.* **1932**, 54, 777.

43. L. Fielding. “Determination of association constants ($K_a$) from solution NMR data”, *Tetrahedron.* **2000**, 56, 6151.

44. M. J. Hynes. “EQNMR-A-Computer-program for the calculation of stability-constants from nuclear-magnetic-resonance chemical-shift data”, *J. Chem. Soc., Dalton Trans.* **1993**, 311.

45. V. Vetrogon, L. G. Lukyanenko, M. J. Schwing-Weill and F. Arnaud-Neu. “A PC compatible computer program for the calculation of equilibrium constants by the simultaneous processing of different sets of experiment results”, *Talanta.* **1994**, 41, 2105.

# APPENDICES

# APPENDIX A

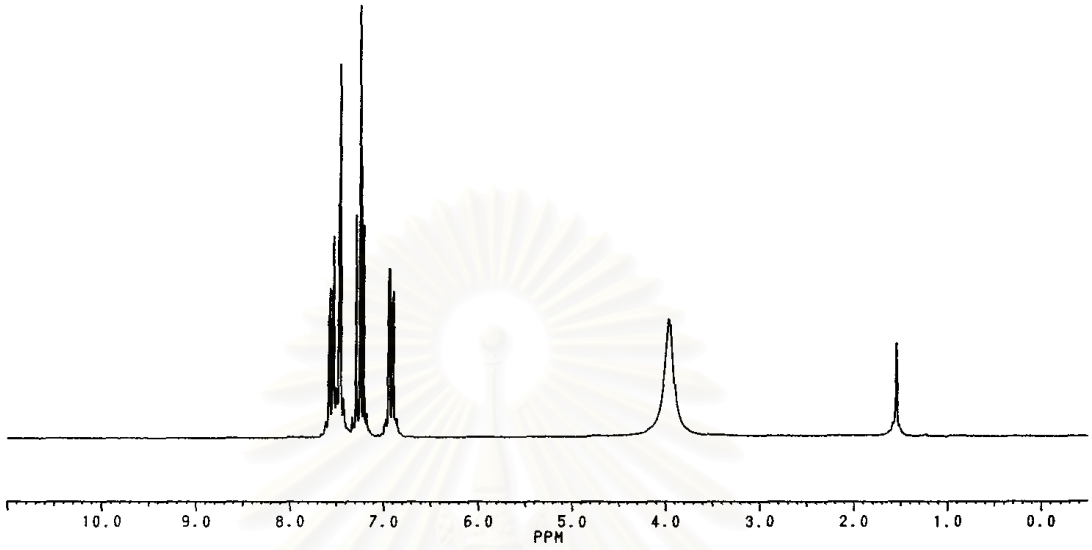



**Figure A.1** The $^{1}$H-NMR spectrum of 3,3′-diaminoazobenzene, **1**, in $CDCl_3$ with 200 MHz.

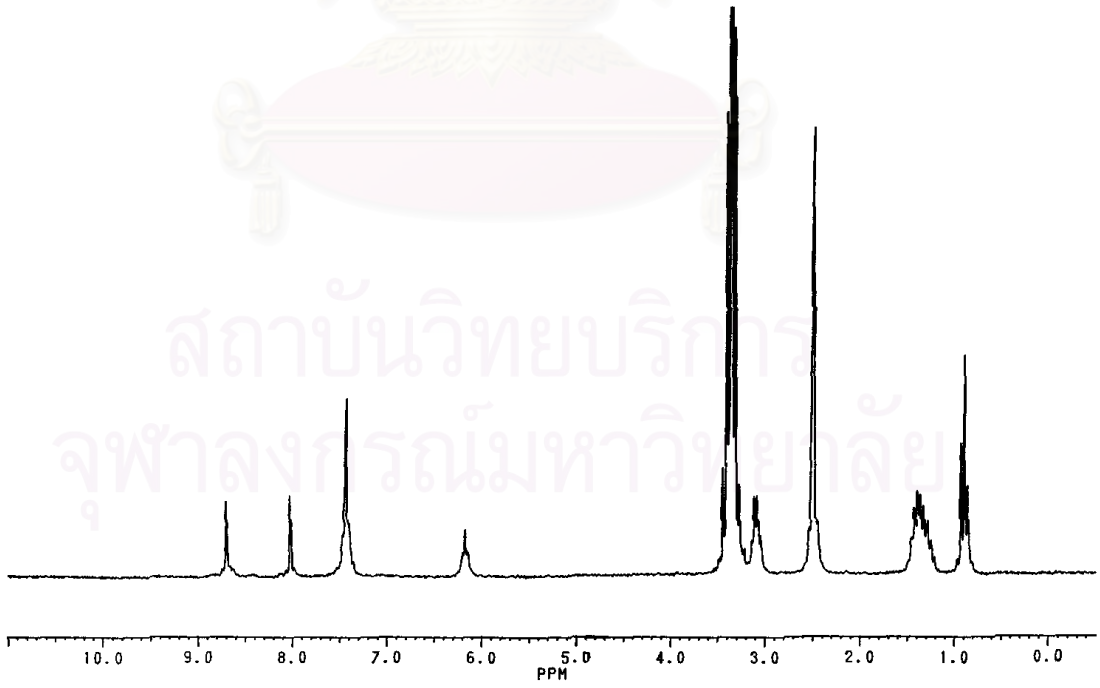



**Figure A.2** The $^{1}$H-NMR spectrum of 3,3′-bis(*N*′-butylureido)azobenzene, **2a**, in DMSO-$d_6$ with 200 MHz.

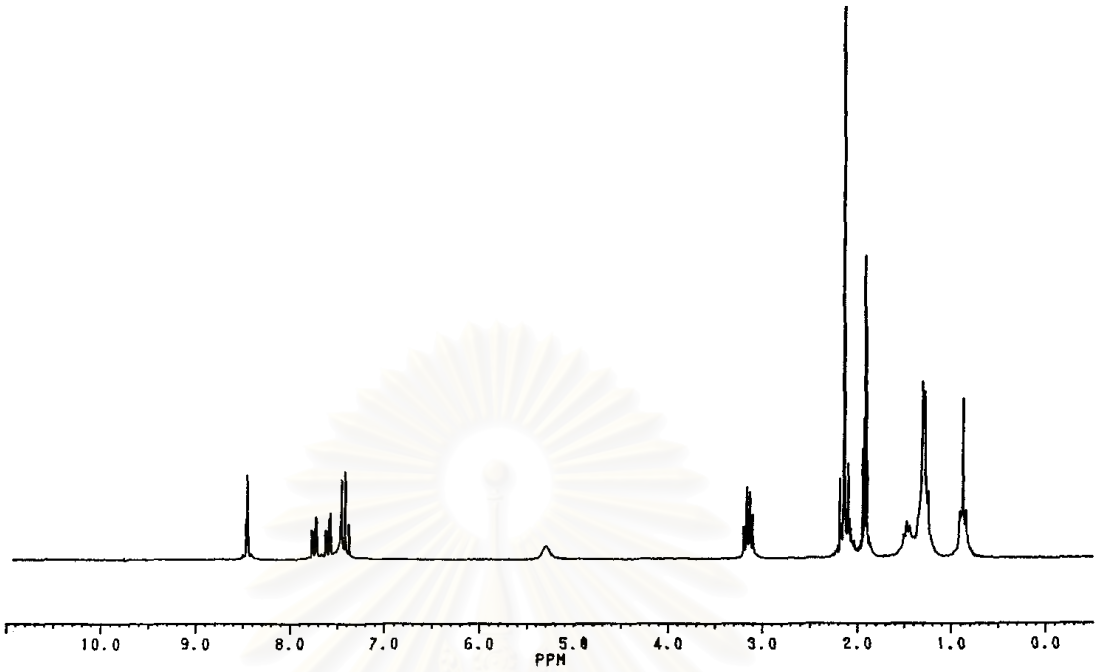



**Figure A.3** The $^{1}$H-NMR spectrum of 3,3′-bis(*N*′-hexylureido)azobenzene, **2b**, in $CD_3CN$ with 200 MHz.

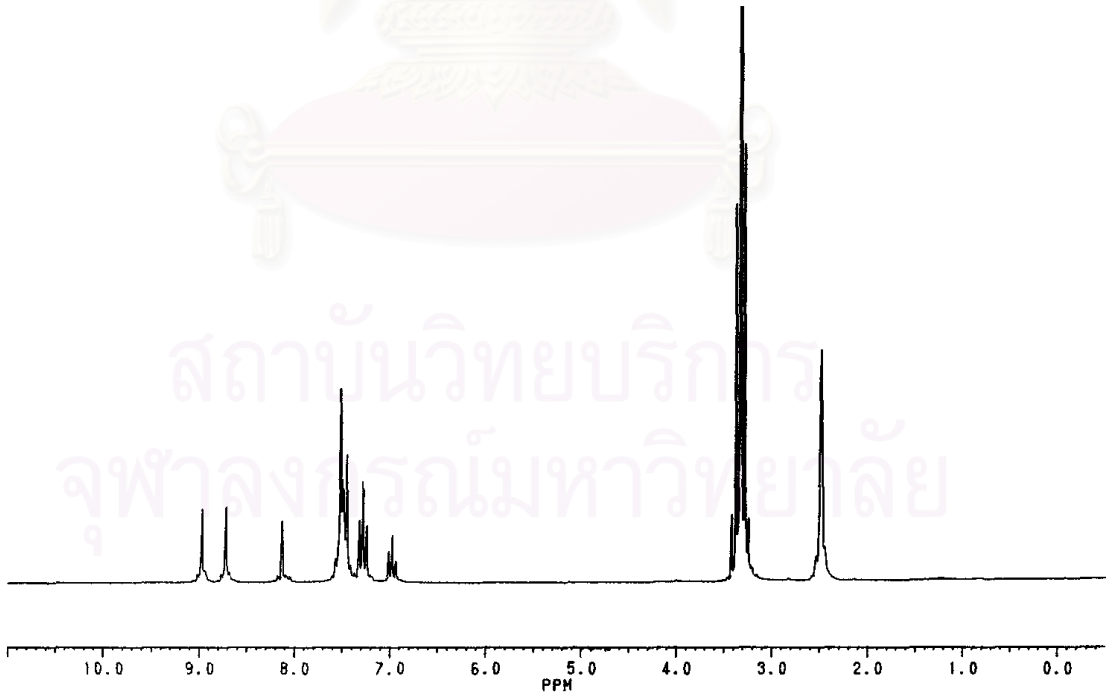



**Figure A.4** The $^{1}$H-NMR spectrum of 3,3′-bis(*N*′-phenylureido)azobenzene, **2c**, in DMSO-$d_6$ with 200MHz.

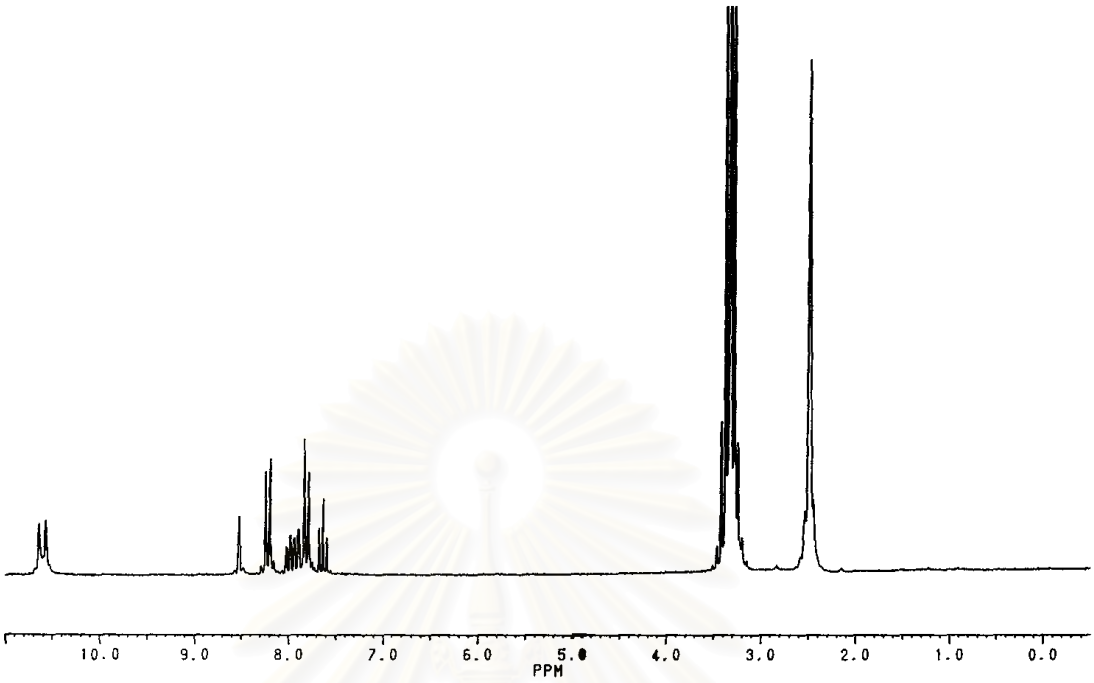



**Figure A.5** The $^{1}$H-NMR spectrum of 3,3′-bis(*N*′-(4-nitrophenyl)thioureido) azobenzene, **2d**, in DMSO-$d_6$ with 200MHz.

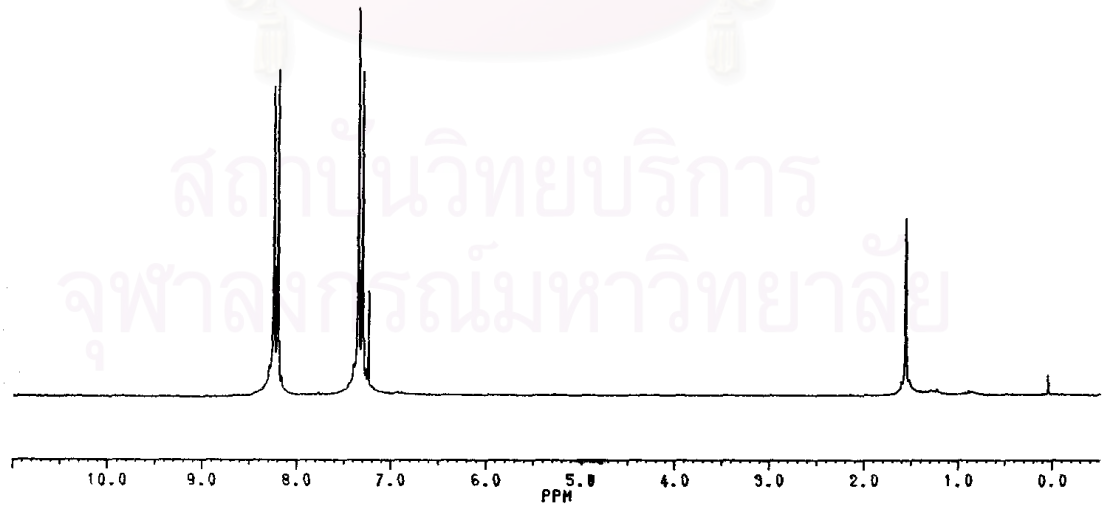



**Figure A.6** The $^{1}$H-NMR spectrum of 4-nitrophenyl thioisocyanate, **3**, in $CDCl_3$ with 200 MHz.

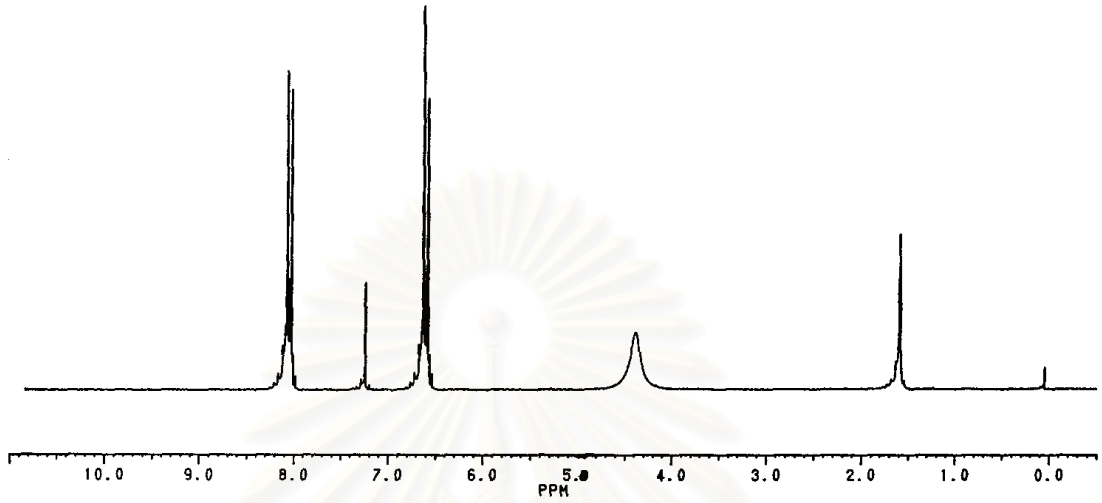



**Figure A.7** The $^{1}$H-NMR spectrum of 4,4′-diaminoazobenzene, **4**, in $CDCl_3$ with 200 MHz.

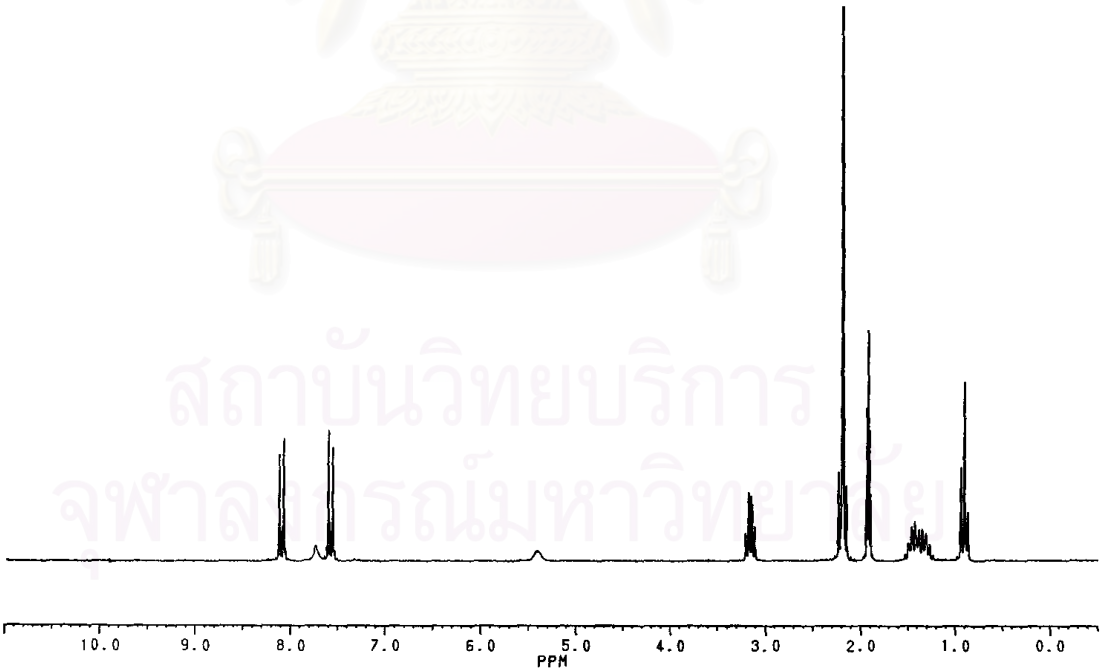



**Figure A.8** The $^{1}$H-NMR spectrum of 4,4′-bis(*N*′-butylureido)azobenzene, **5a**, in $CD_3CN$ with 200MHz.

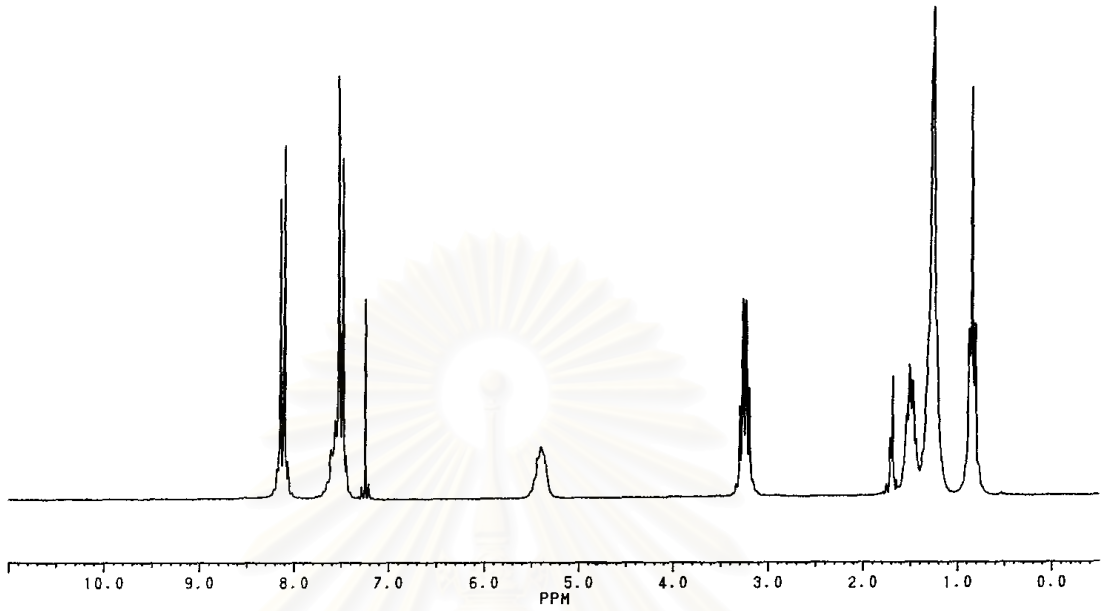



**Figure A.9** The $^{1}$H-NMR spectrum of 4,4′-bis(*N*′-hexylureido)azobenzene, **5b**, in $CDCl_3$ with 200 MHz.

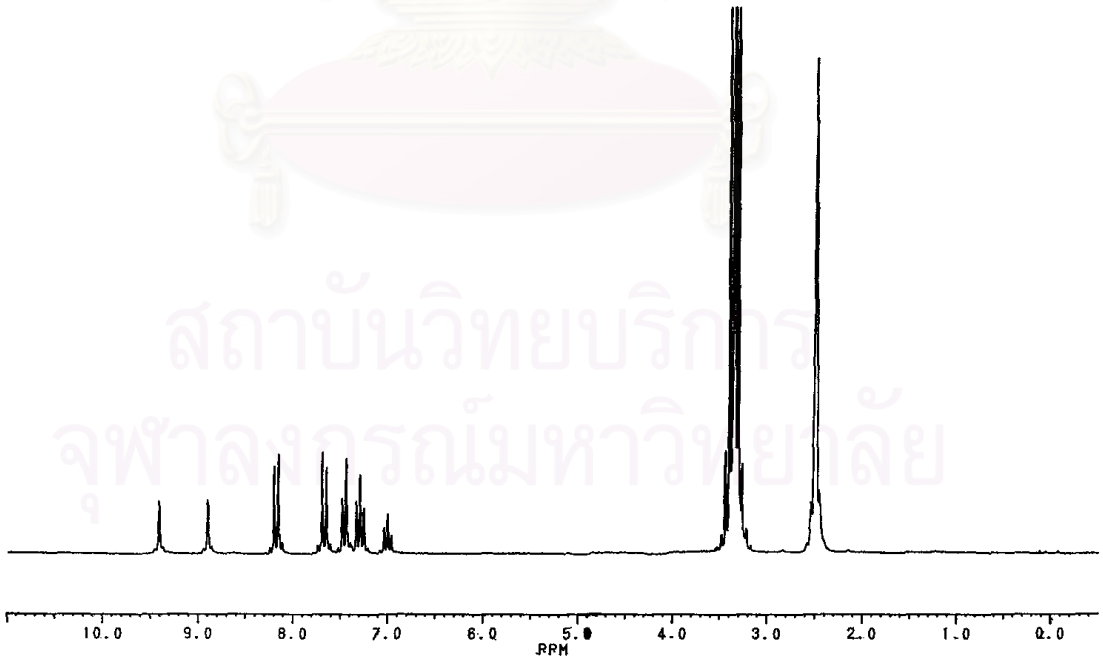



**Figure A.10** The $^{1}$H-NMR spectrum of 4,4′-bis(*N*′-phenylureido)azobenzene, **5c**, in DMSO-$d_6$ with 200 MHz.

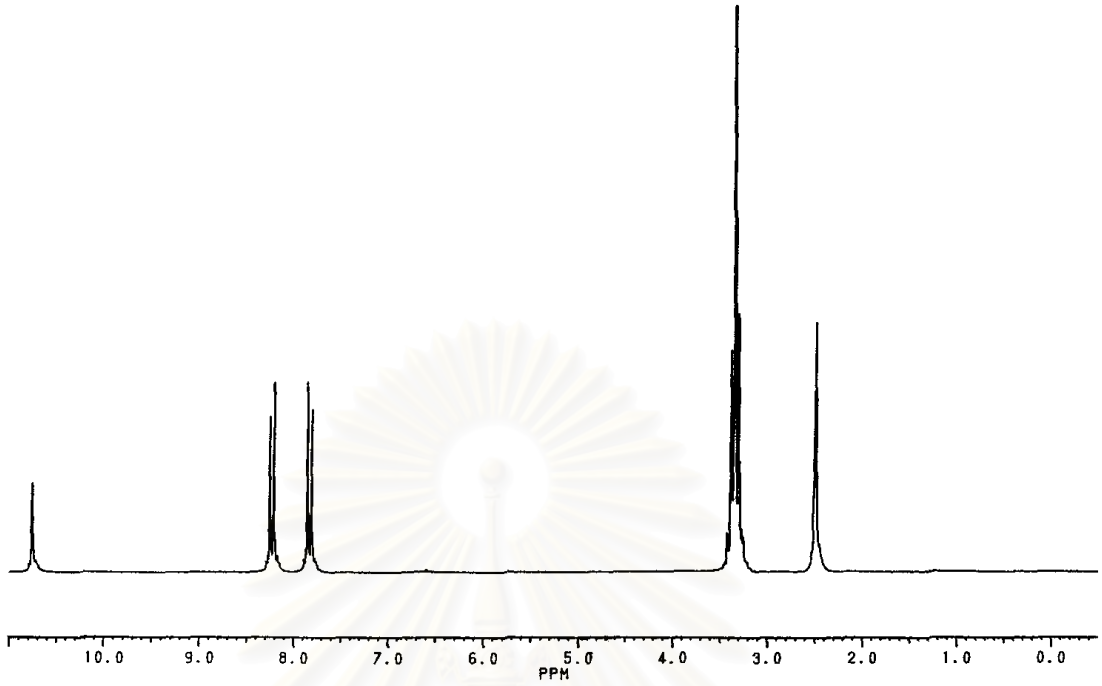



**Figure A.11** The $^{1}$H-NMR spectrum of 4,4′-bis(*N*′-(4-nitrophenyl)thioureido) azobenzene, **5d**, in DMSO-$d_6$ with 200 MHz.

# APPENDIX B

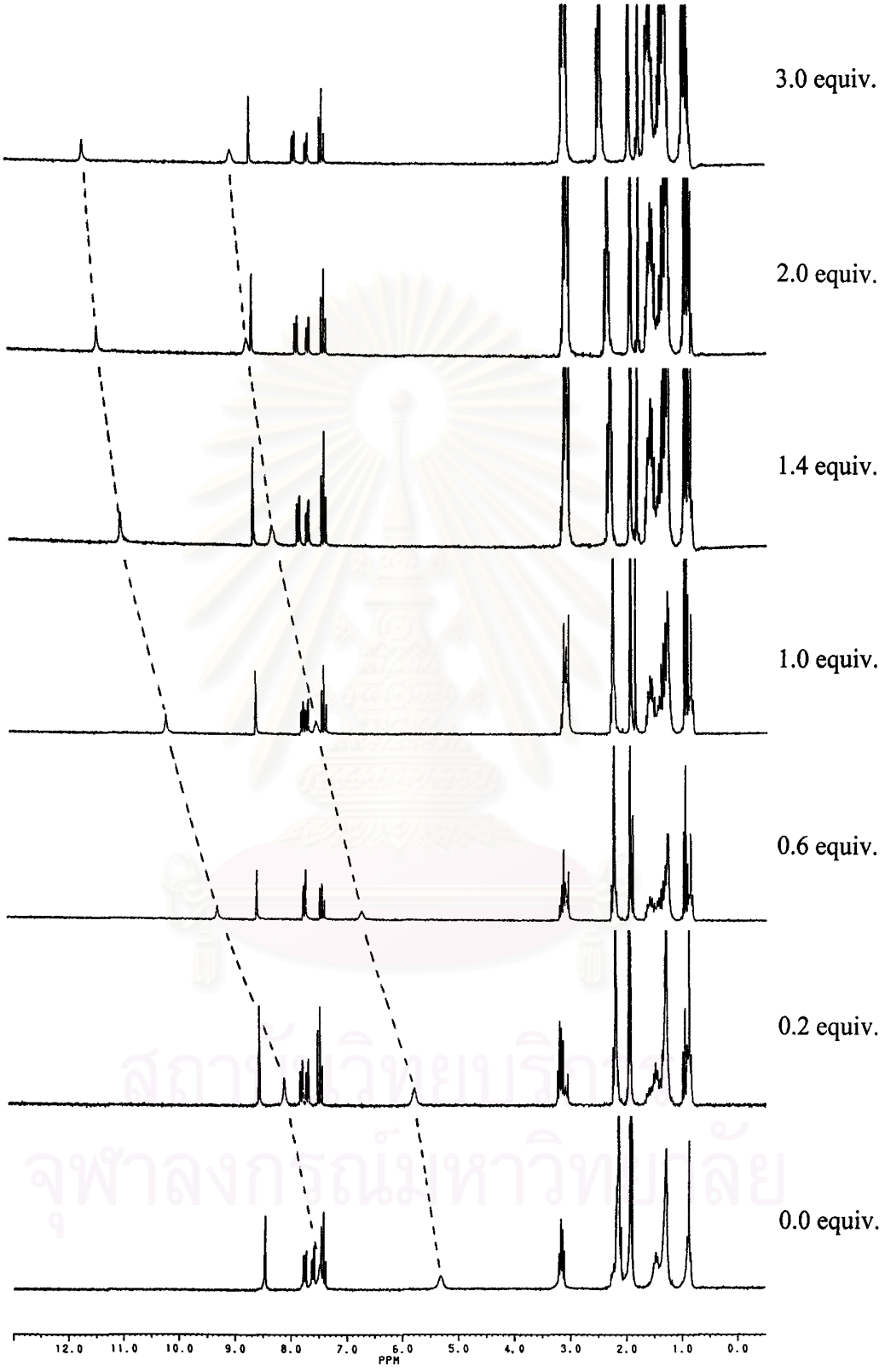



**Figure B.1** $^{1}$H-NMR spectra of **2b** and acetate in $CD_3CN$ with 200 MHz.

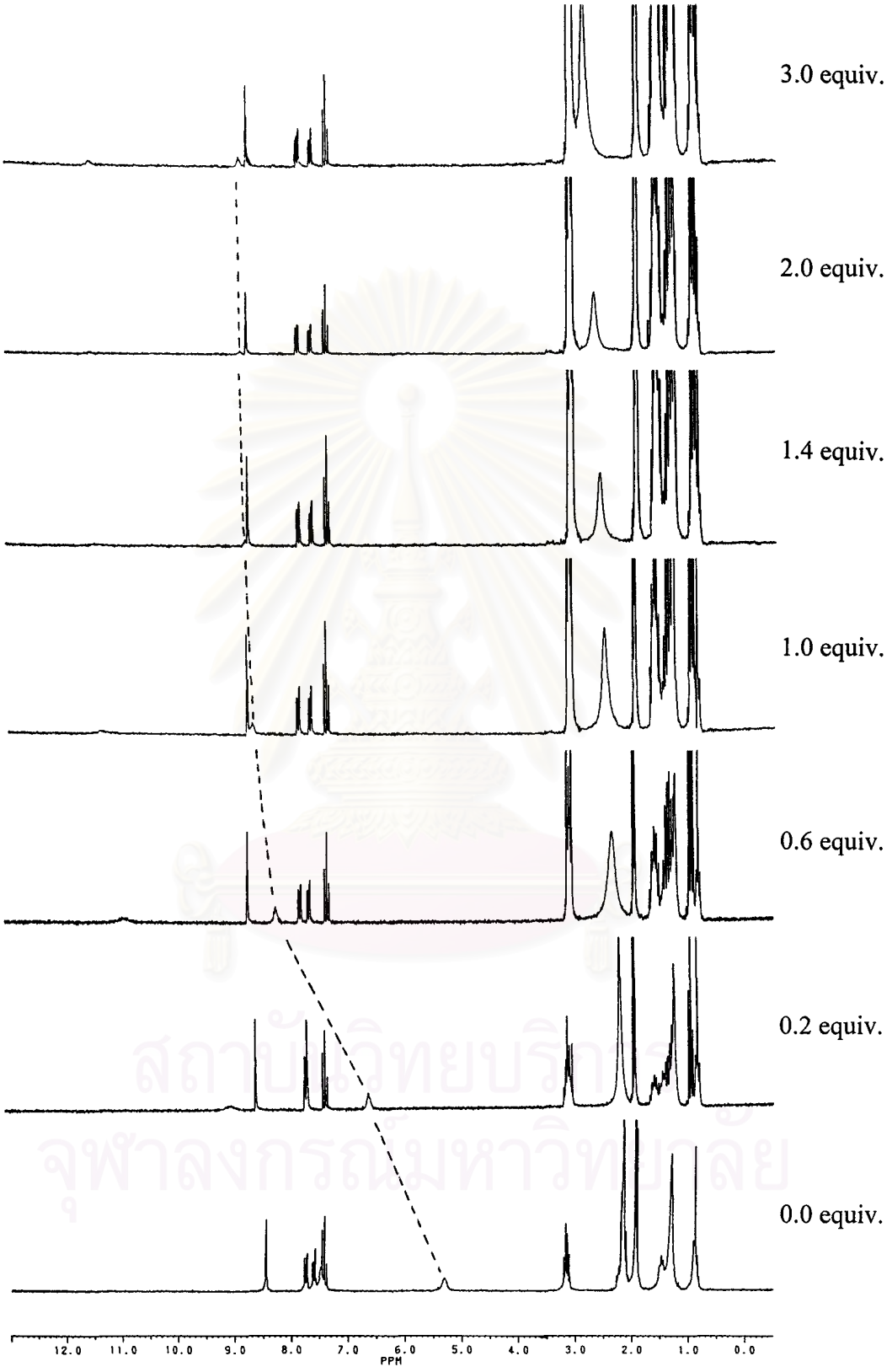



**Figure B.2** $^{1}$H-NMR spectra of **2b** and oxalate in $CD_3CN$ with 200 MHz.

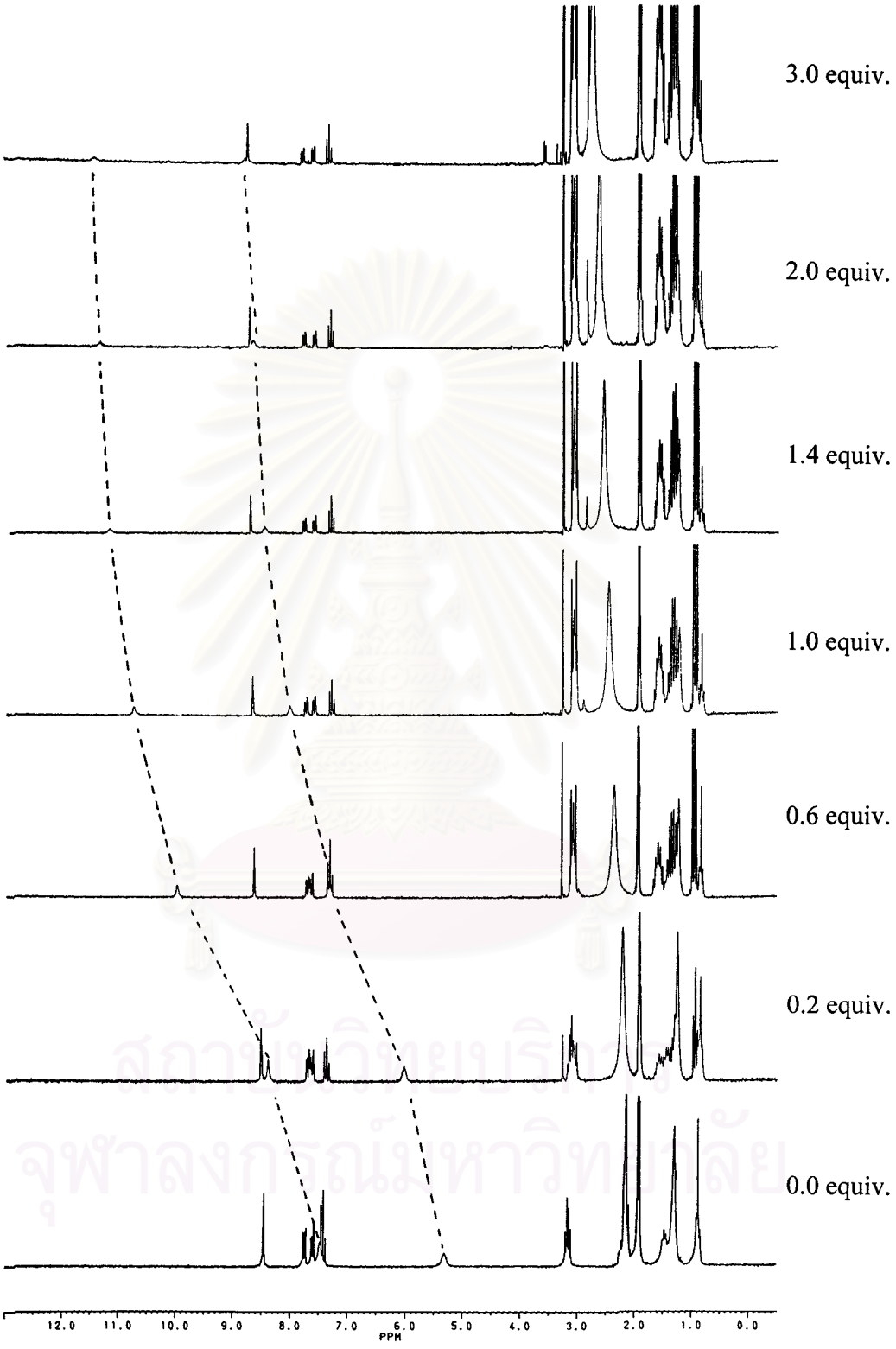



**Figure B.3** $^{1}$H-NMR spectra of **2b** and malonate in $CD_3CN$ with 200 MHz.

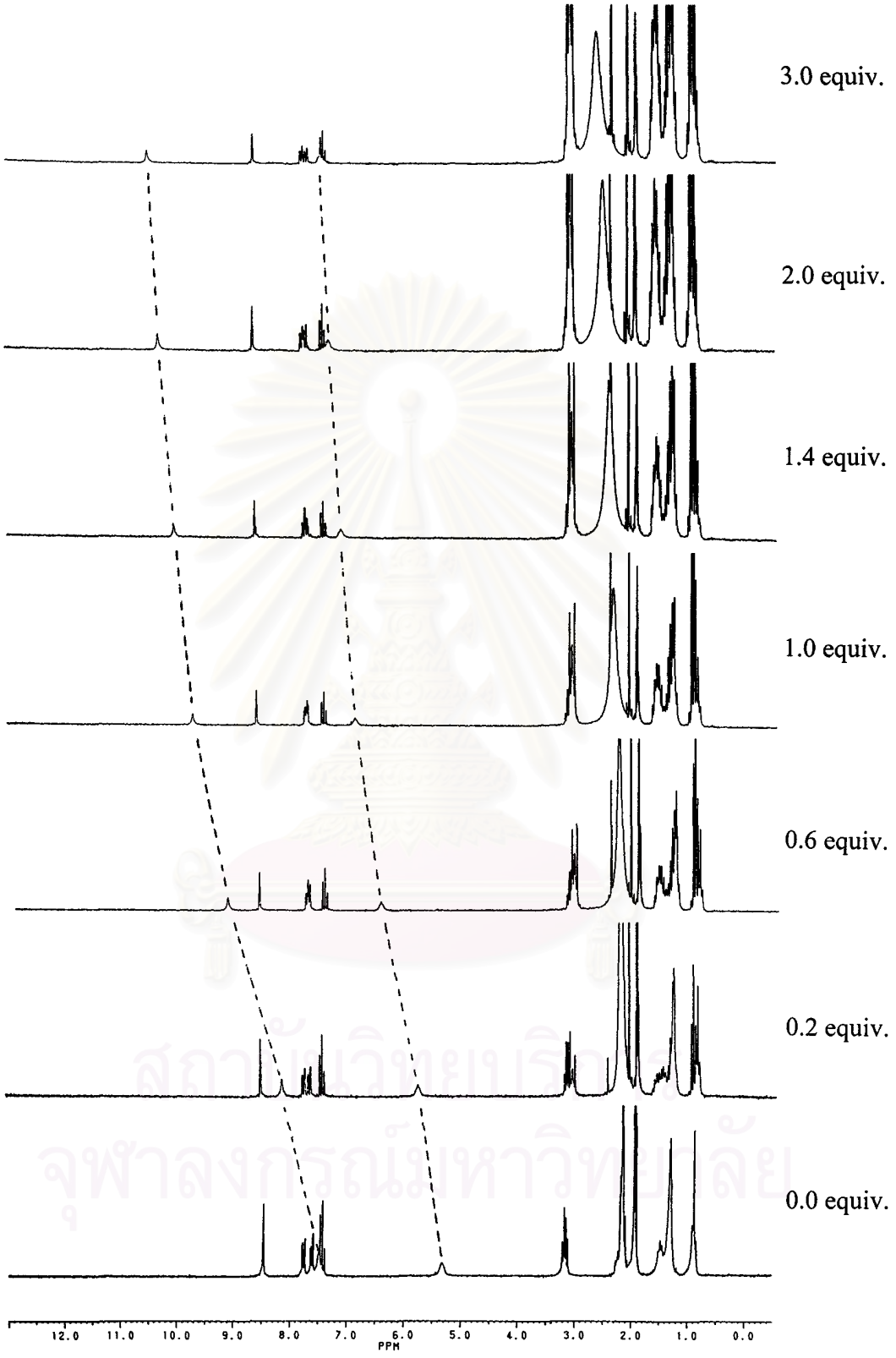



**Figure B.4** $^{1}$H-NMR spectra of **2b** and succinate in $CD_3CN$ with 200 MHz.

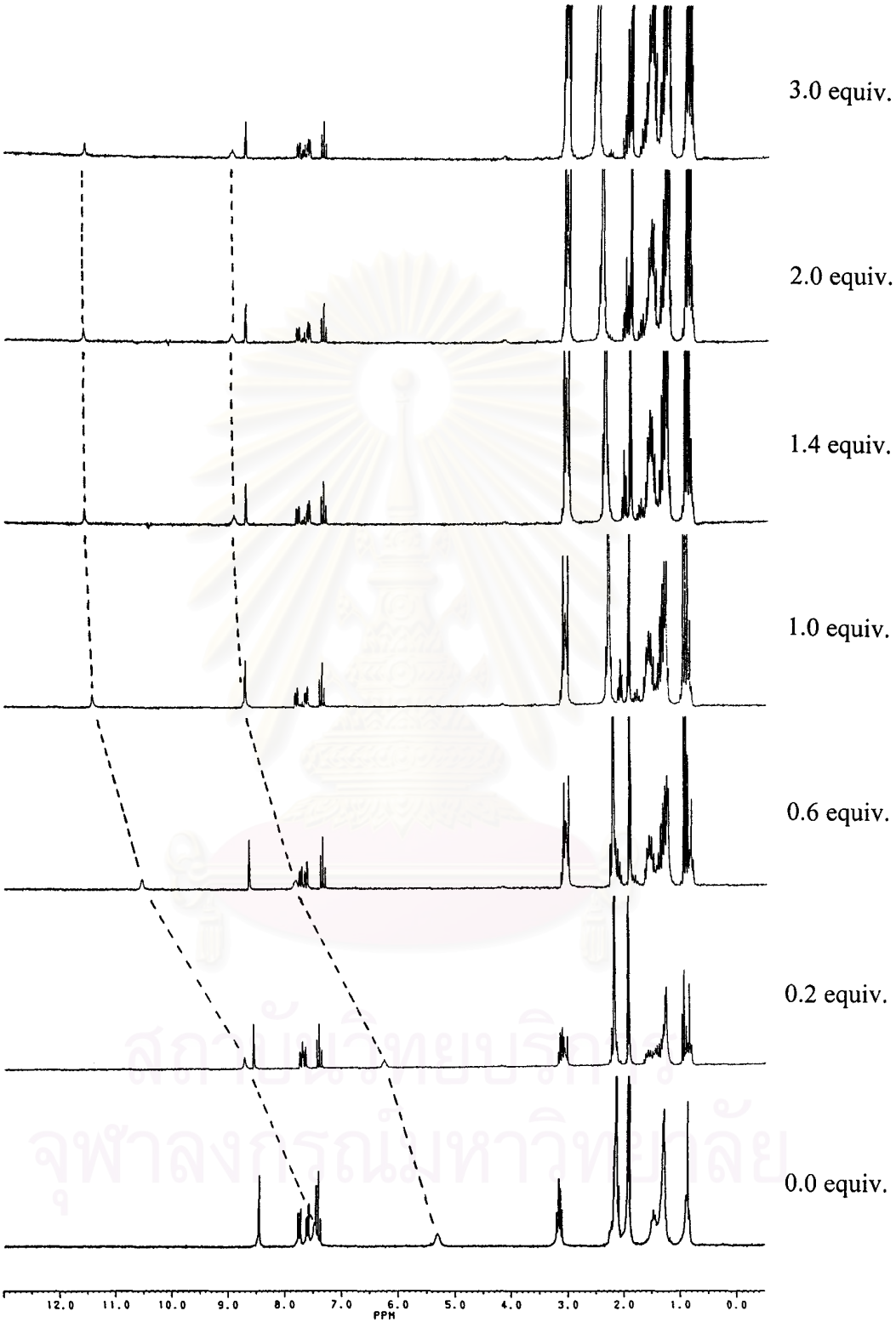



**Figure B.5** $^{1}$H-NMR spectra of **2b** and glutarate in $CD_3CN$ with 200 MHz.

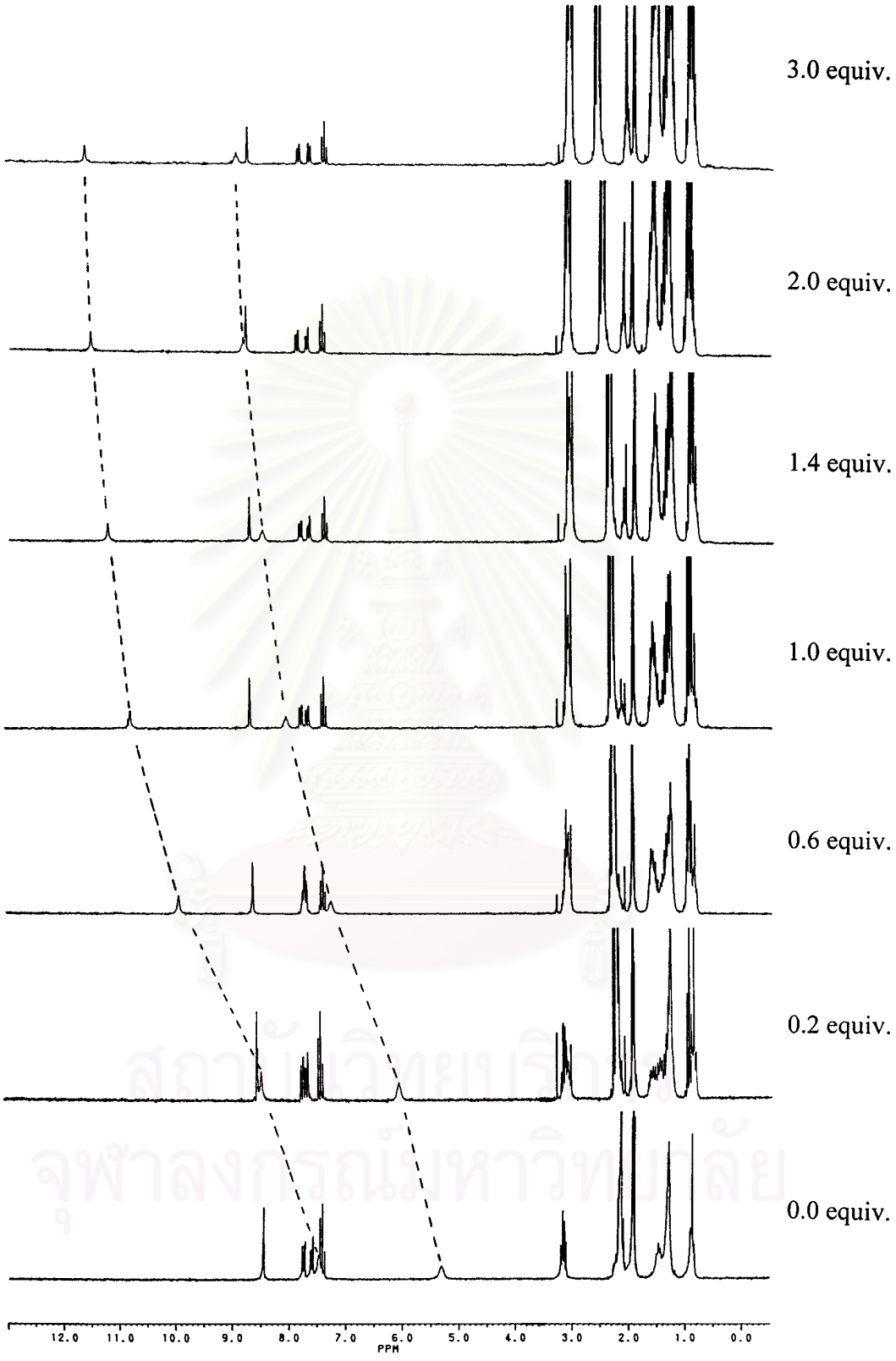



**Figure B.6** $^{1}$H-NMR spectra of **2b** and adipate in $CD_3CN$ with 200 MHz.

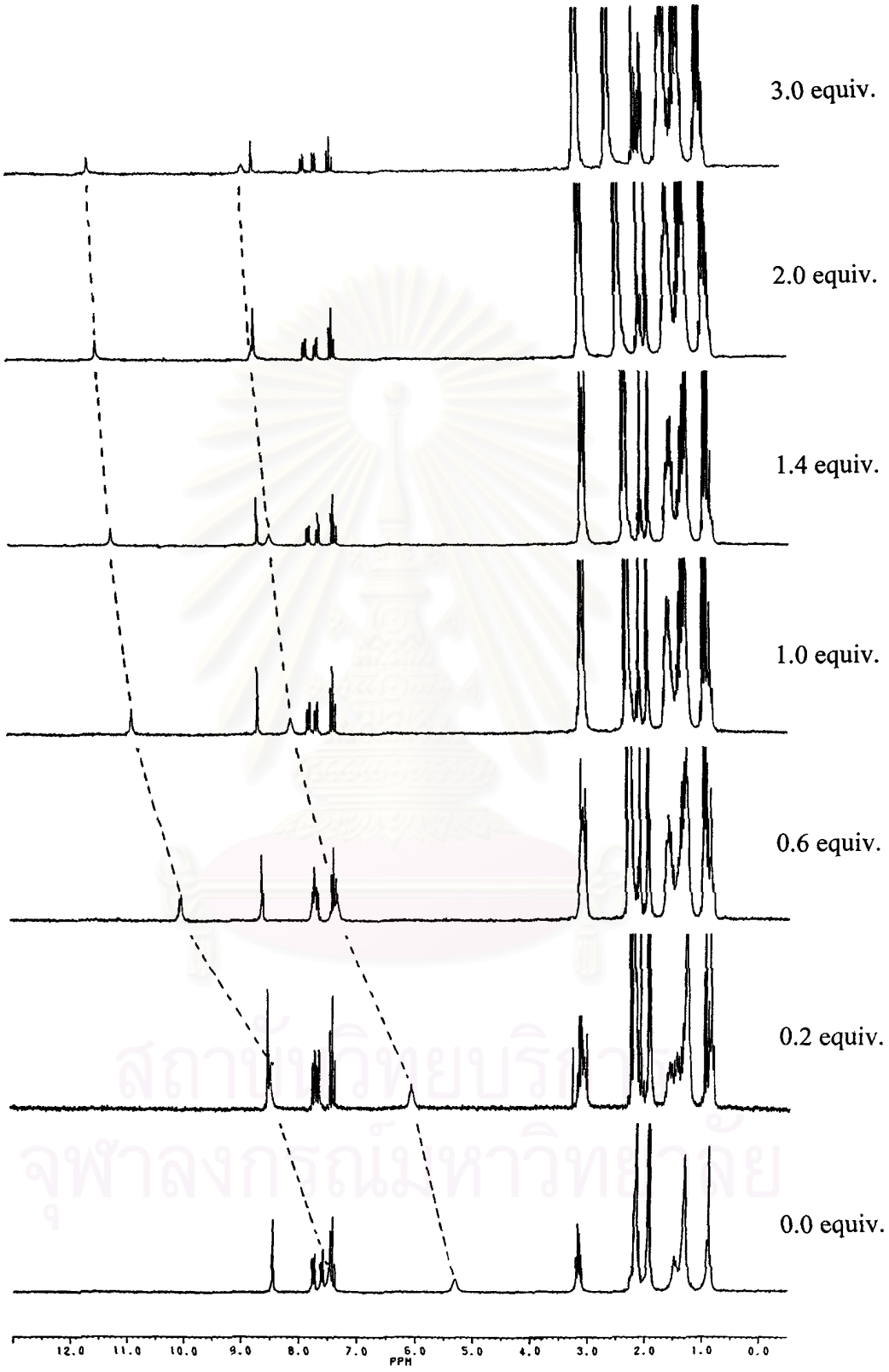



**Figure B.7** $^{1}$H-NMR spectra of **2b** and pimelate in $CD_3CN$ with 200 MHz.

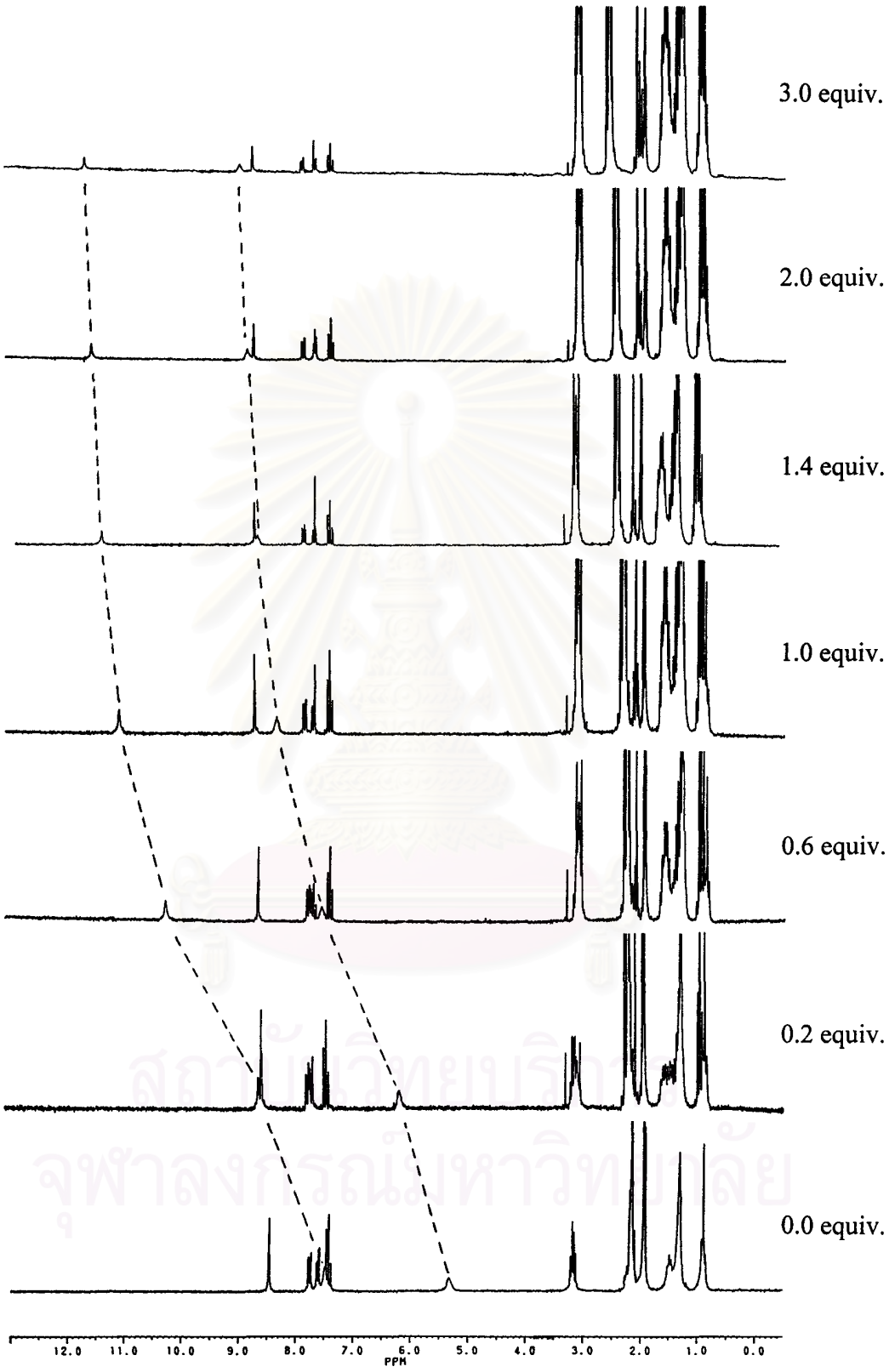



**Figure B.8** $^{1}$H-NMR spectra of **2b** and azelate in $CD_3CN$ with 200 MHz.

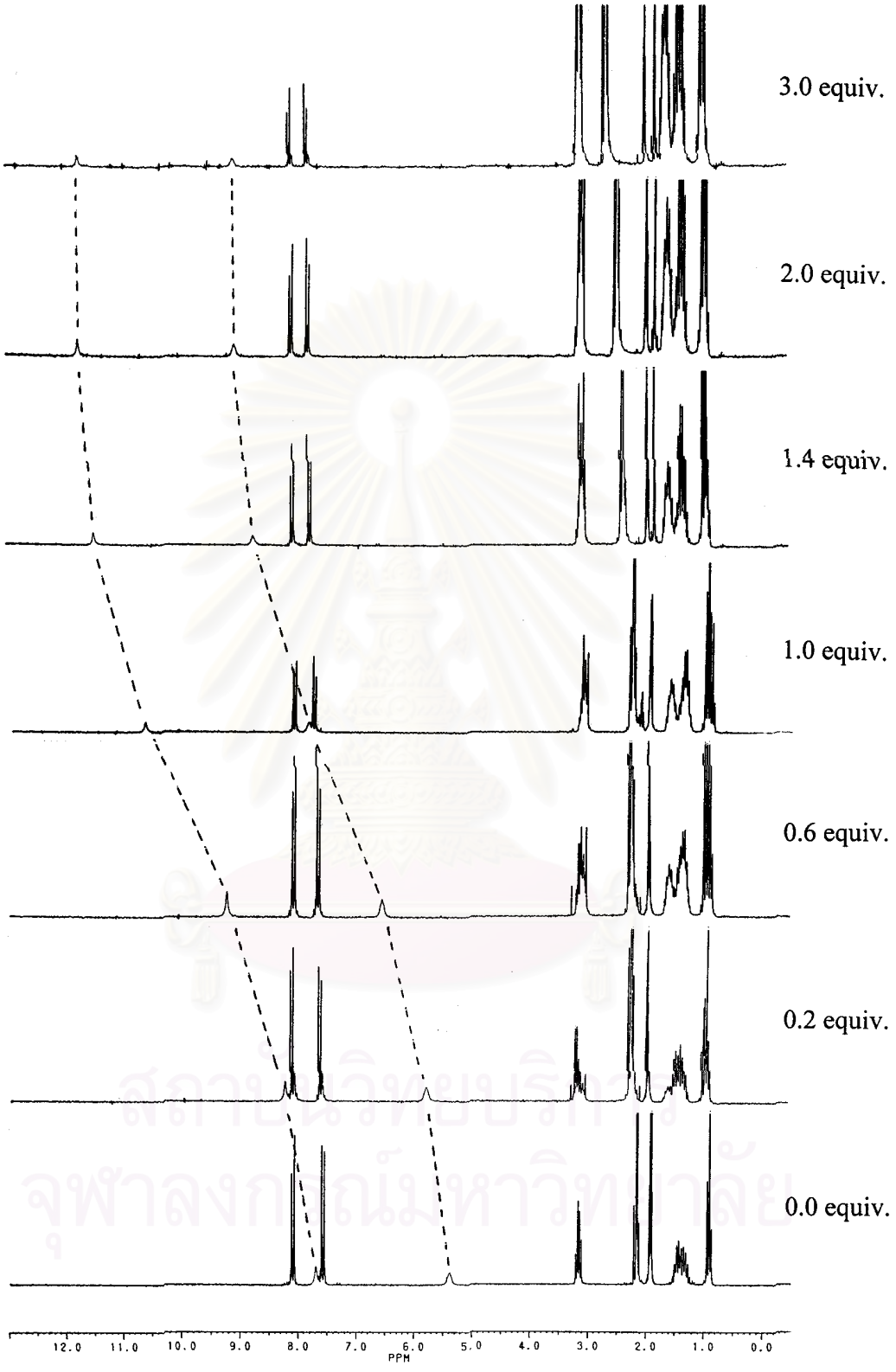



**Figure B.9** $^{1}$H-NMR spectra of **5a** and acetate in $CD_3CN$ with 200 MHz.

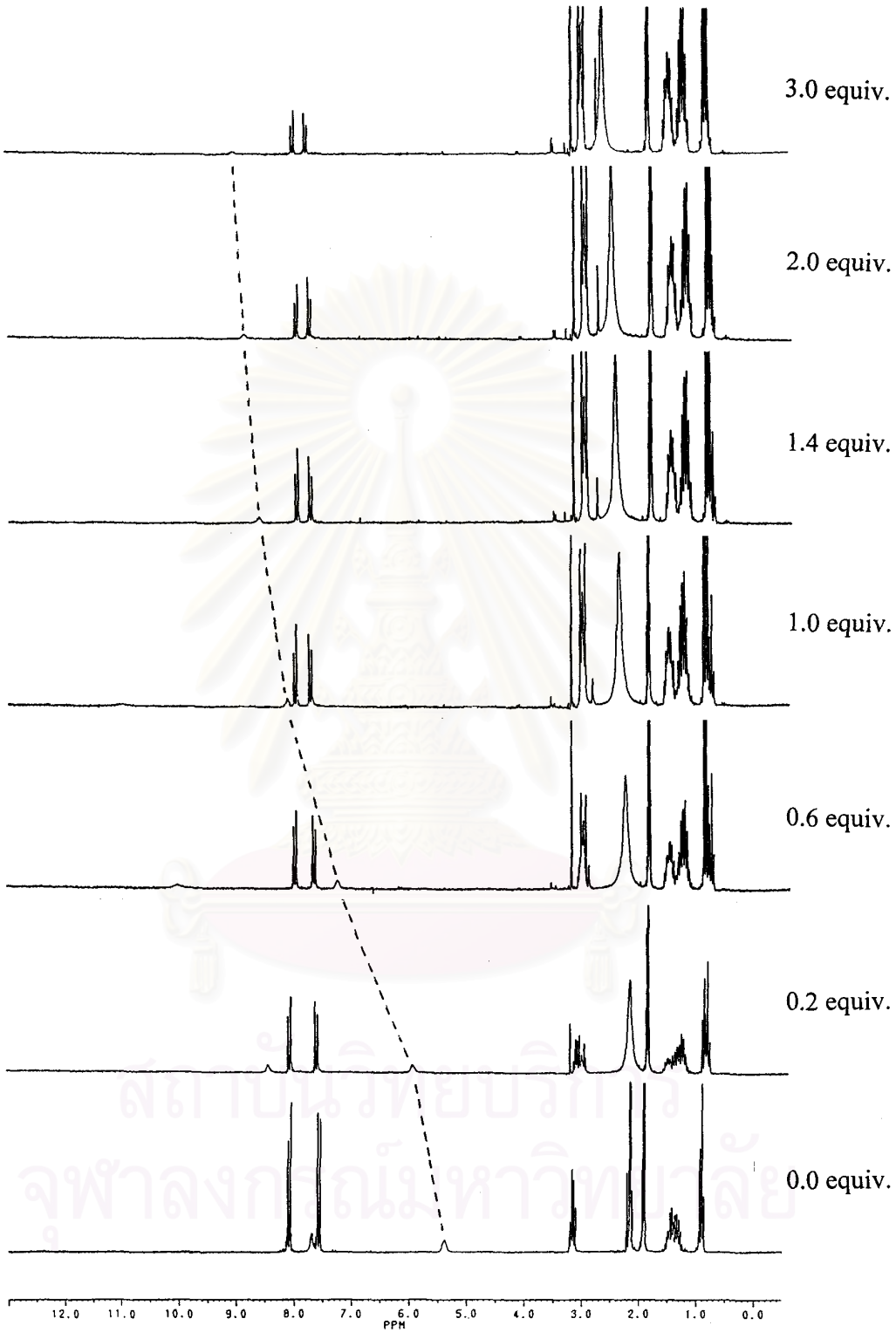



**Figure B.10** $^{1}$H-NMR spectra of **5a** and oxalate in $CD_3CN$ with 200 MHz.

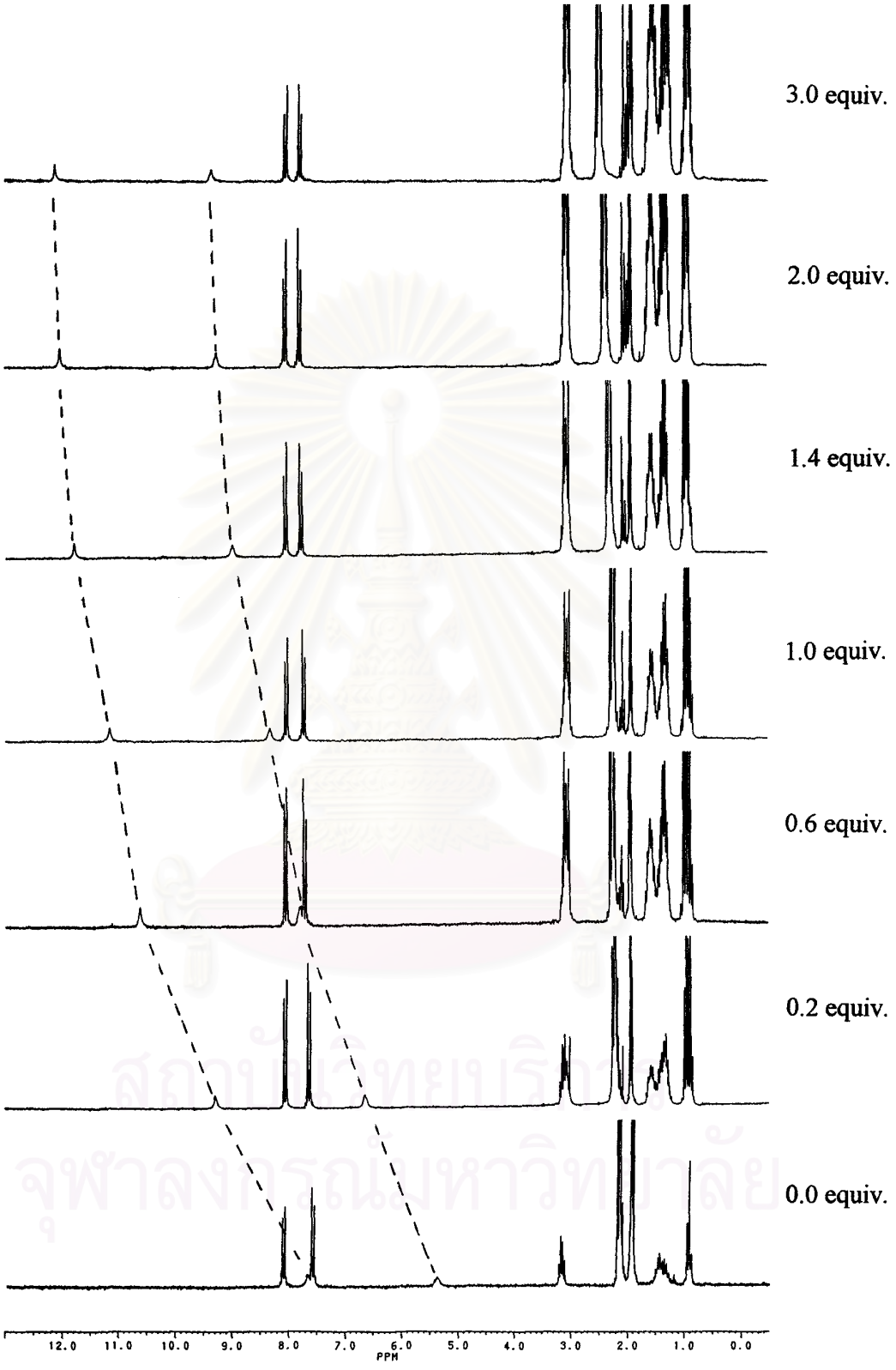



**Figure B.11** $^{1}$H-NMR spectra of **5a** and malonate in $CD_3CN$ with 200 MHz.

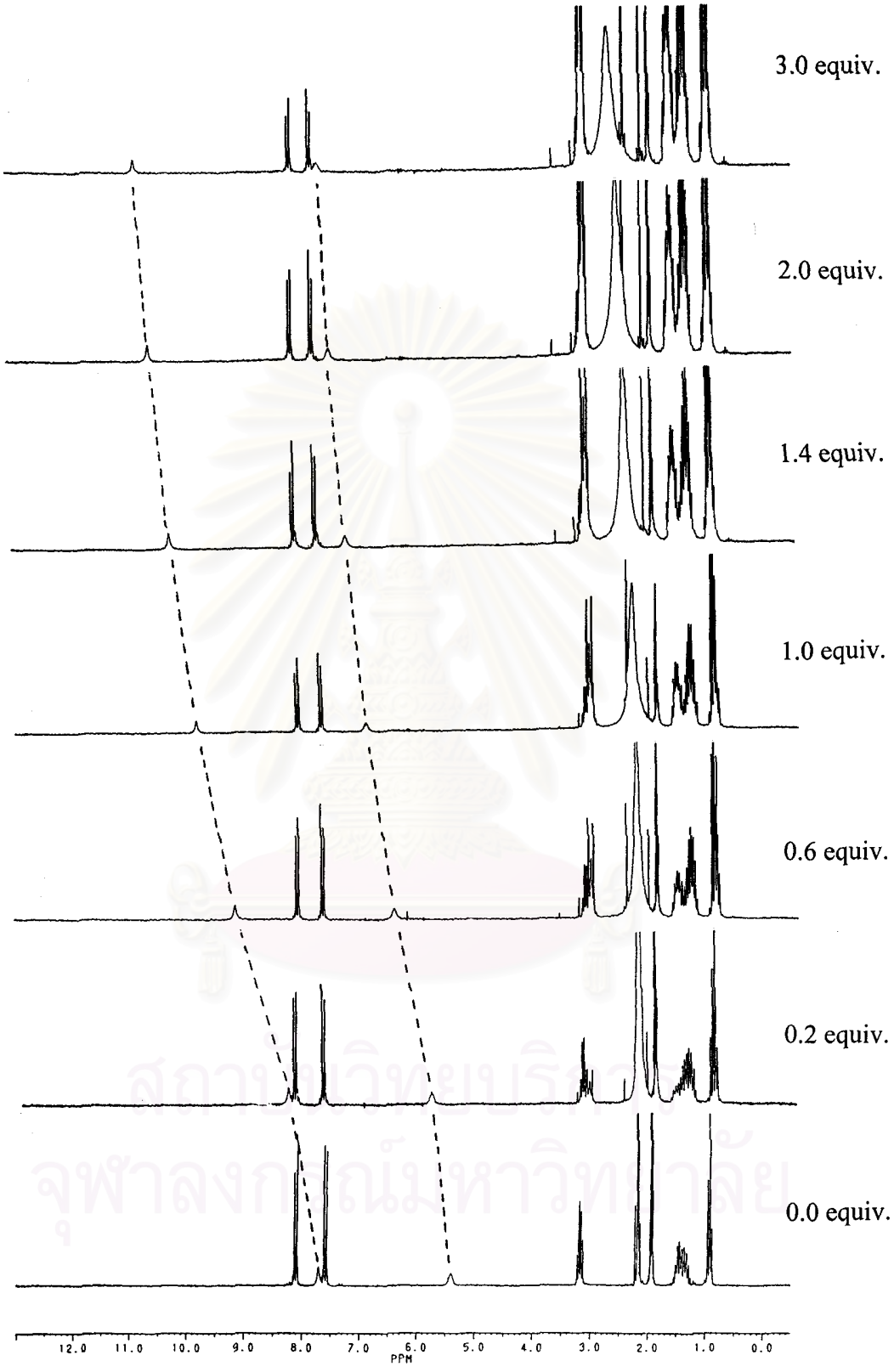



**Figure B.12** $^{1}$H-NMR spectra of **5a** and succinate in $CD_3CN$ with 200 MHz.

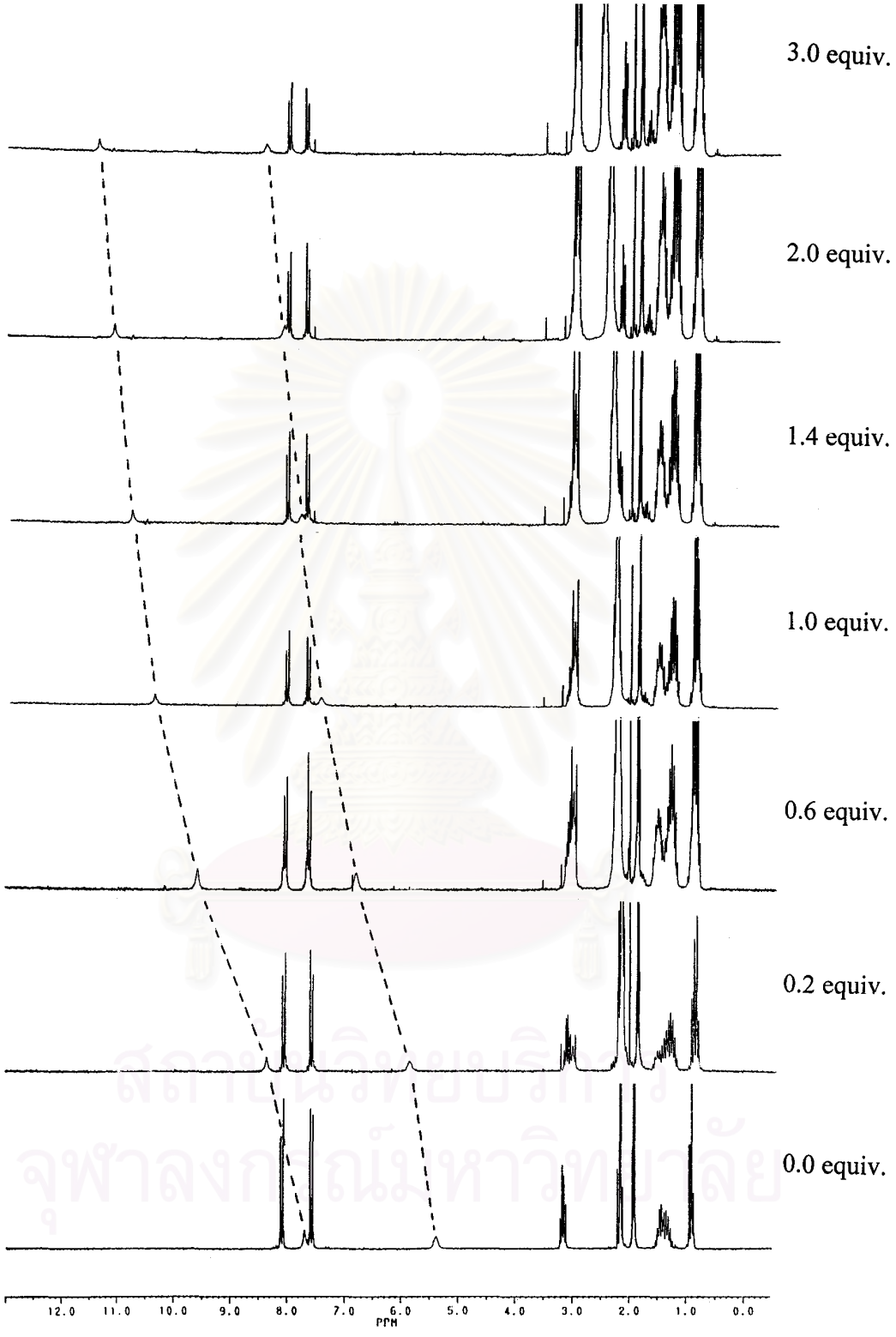



**Figure B.13** $^{1}$H-NMR spectra of **5a** and glutarate in $CD_3CN$ with 200 MHz.

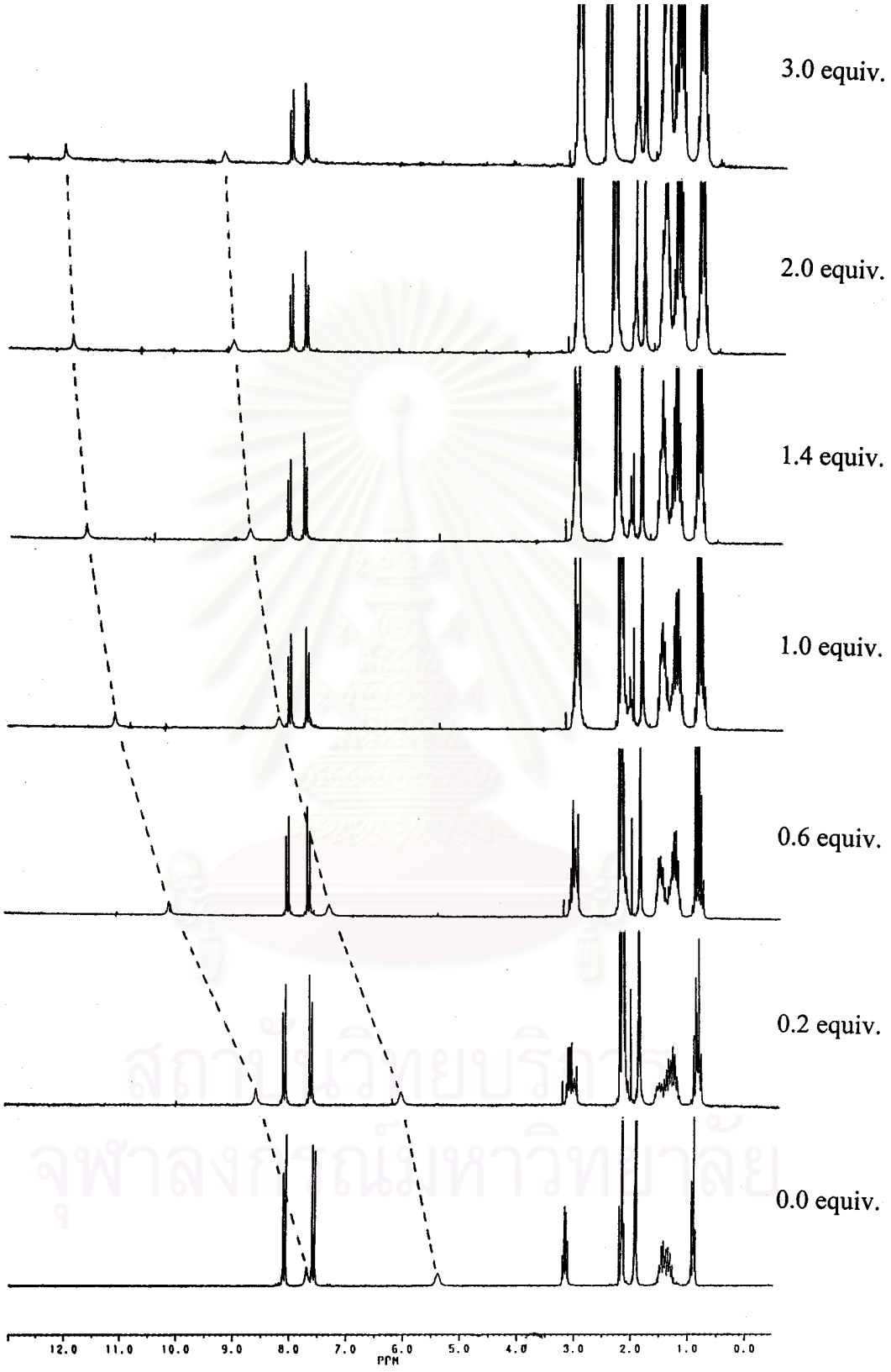



**Figure B.14** $^{1}$H-NMR spectra of **5a** and adipate in $CD_3CN$ with 200 MHz.

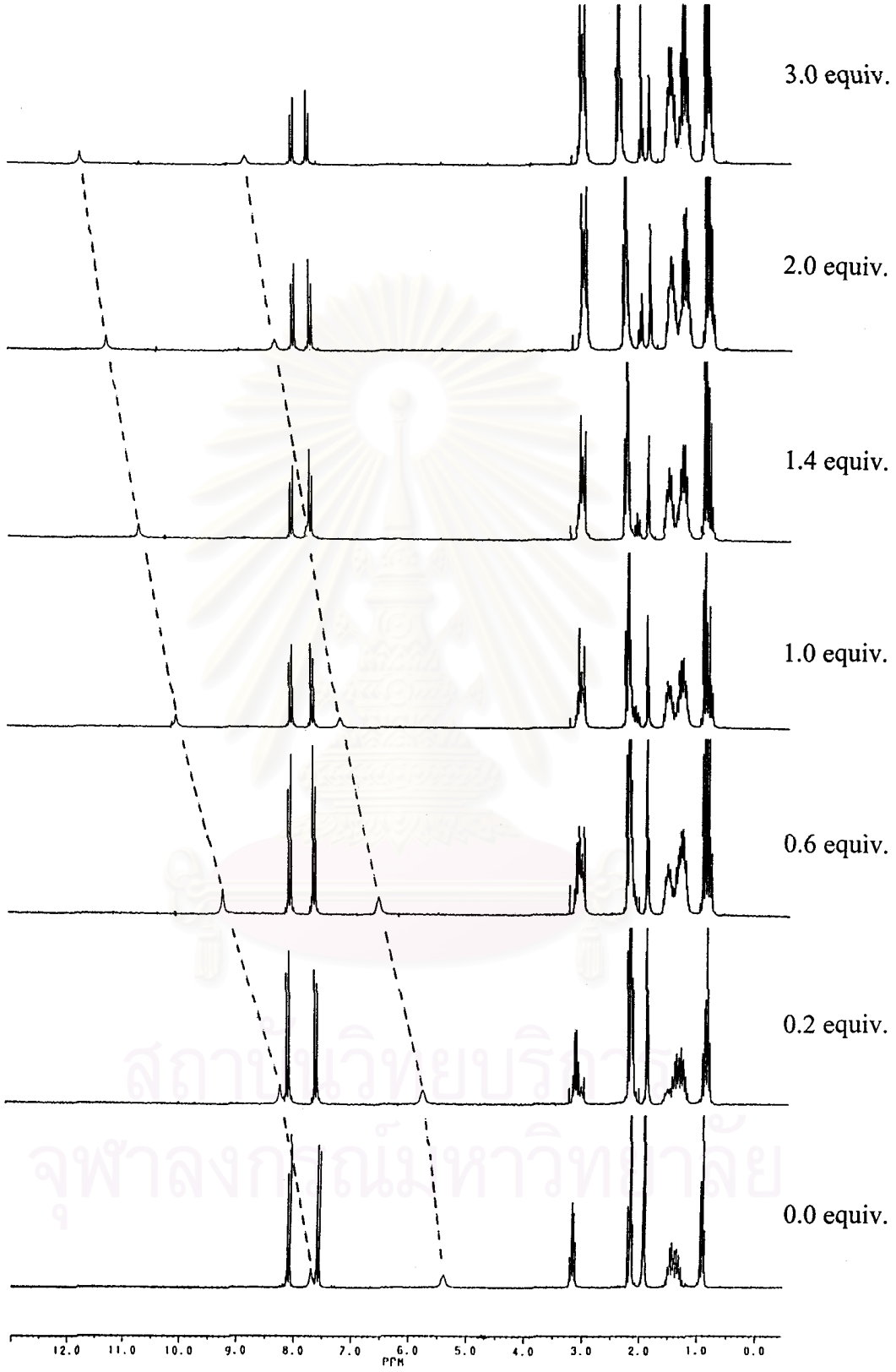



**Figure B.15** $^{1}$H-NMR spectra of **5a** and pimelate in $CD_3CN$ with 200 MHz.

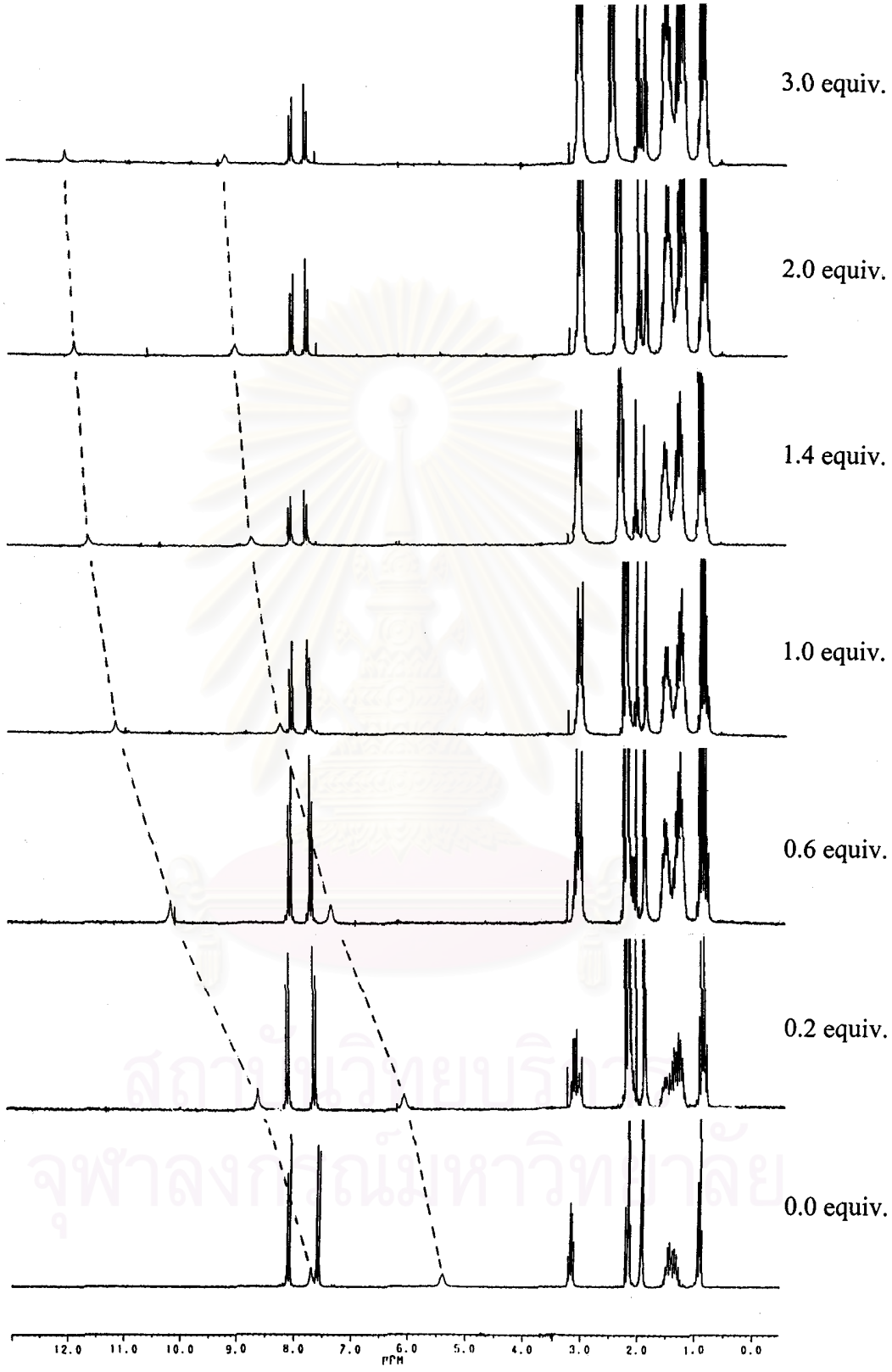



**Figure B.16** $^{1}$H-NMR spectra of **5a** and azelate in $CD_3CN$ with 200 MHz.

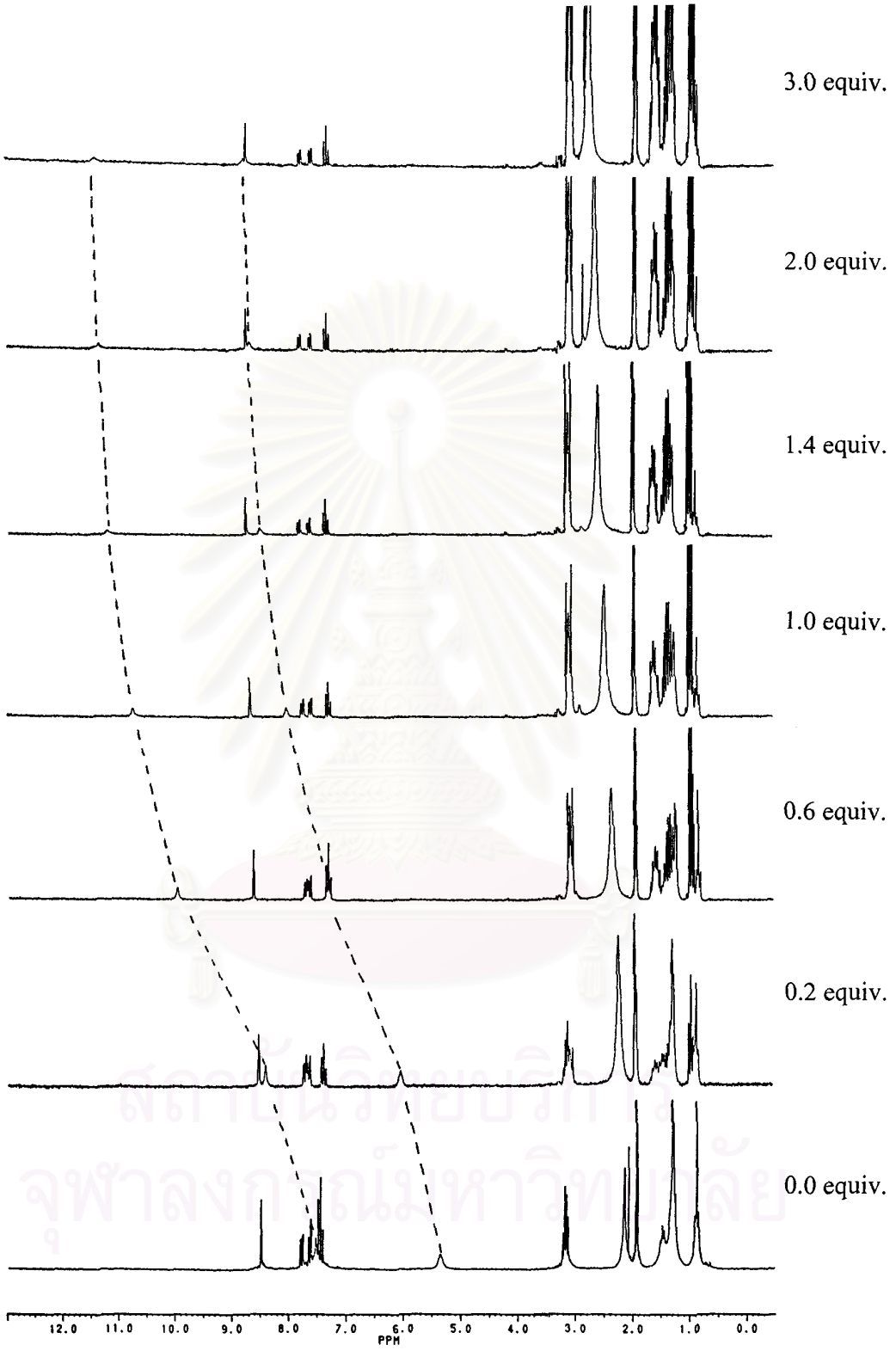



**Figure B.17** $^{1}$H-NMR spectra of **2b** (after irradiation) and acetate in $CD_3CN$ with 200 MHz.

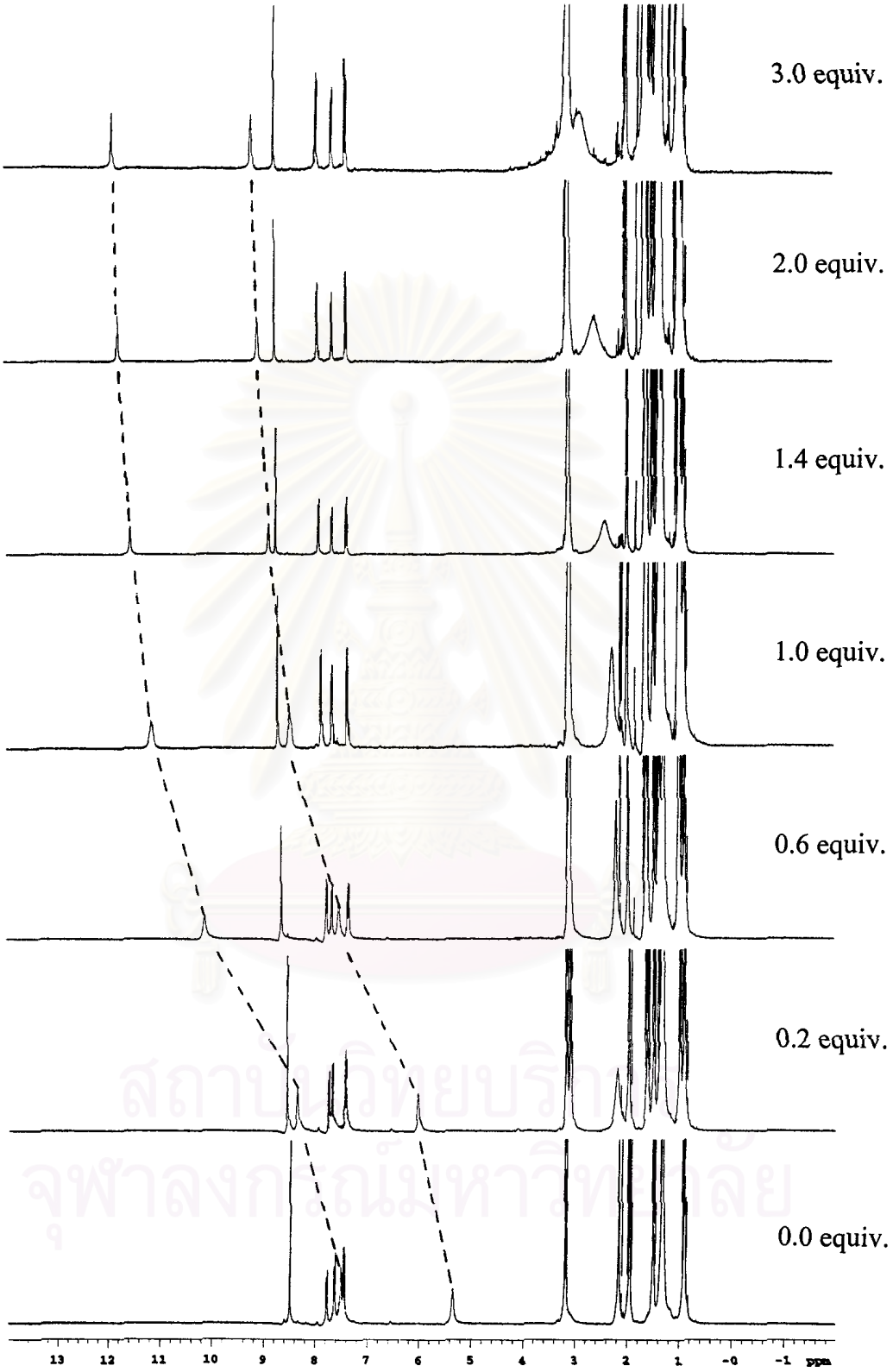



**Figure B.18** $^{1}$H-NMR spectra of **2b** (after irradiation) and oxalate in $CD_3CN$ with 400 MHz.

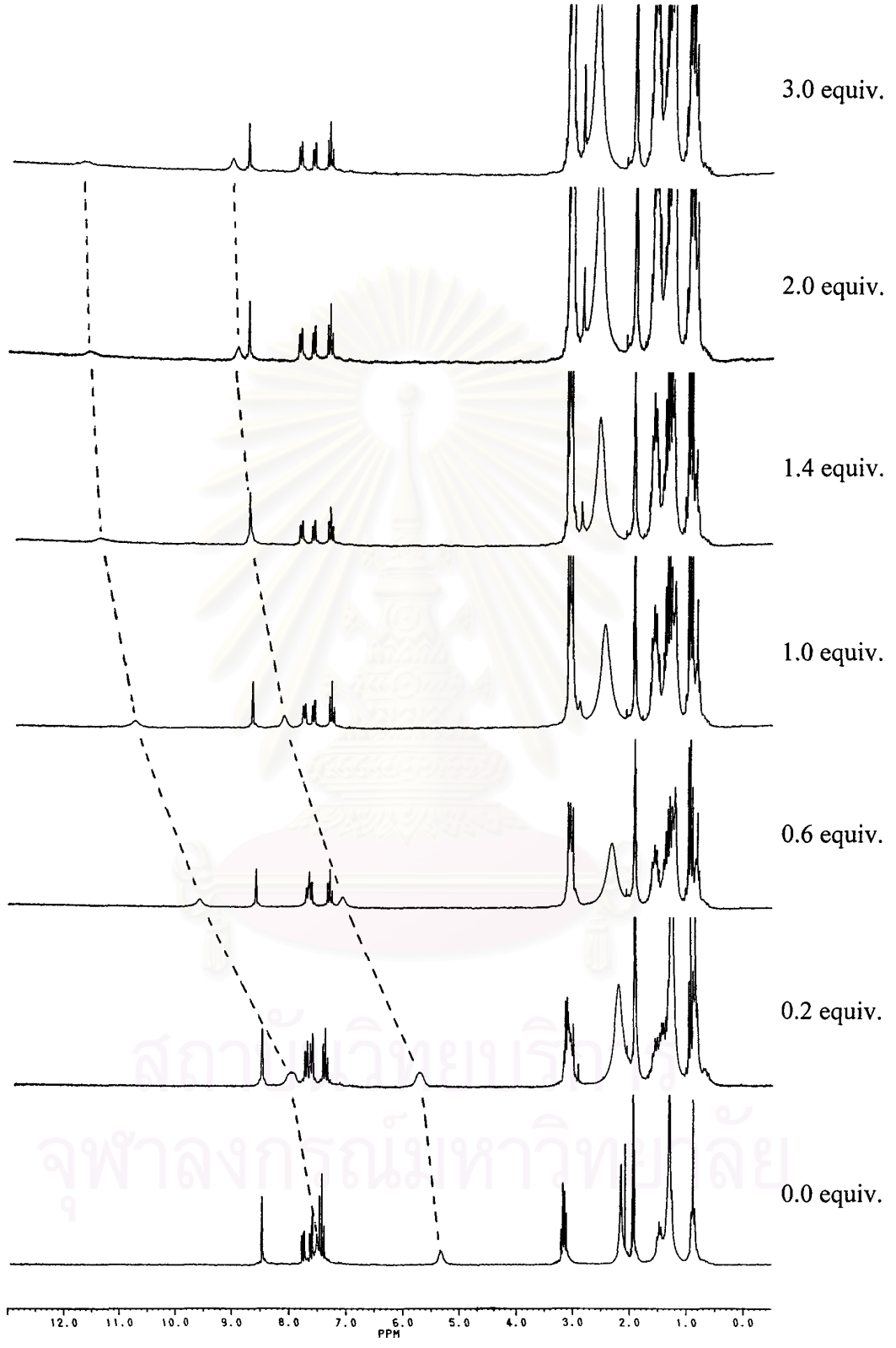



**Figure B.19** $^{1}$H-NMR spectra of **2b** (after irradiation) and malonate in $CD_3CN$ with 200 MHz.

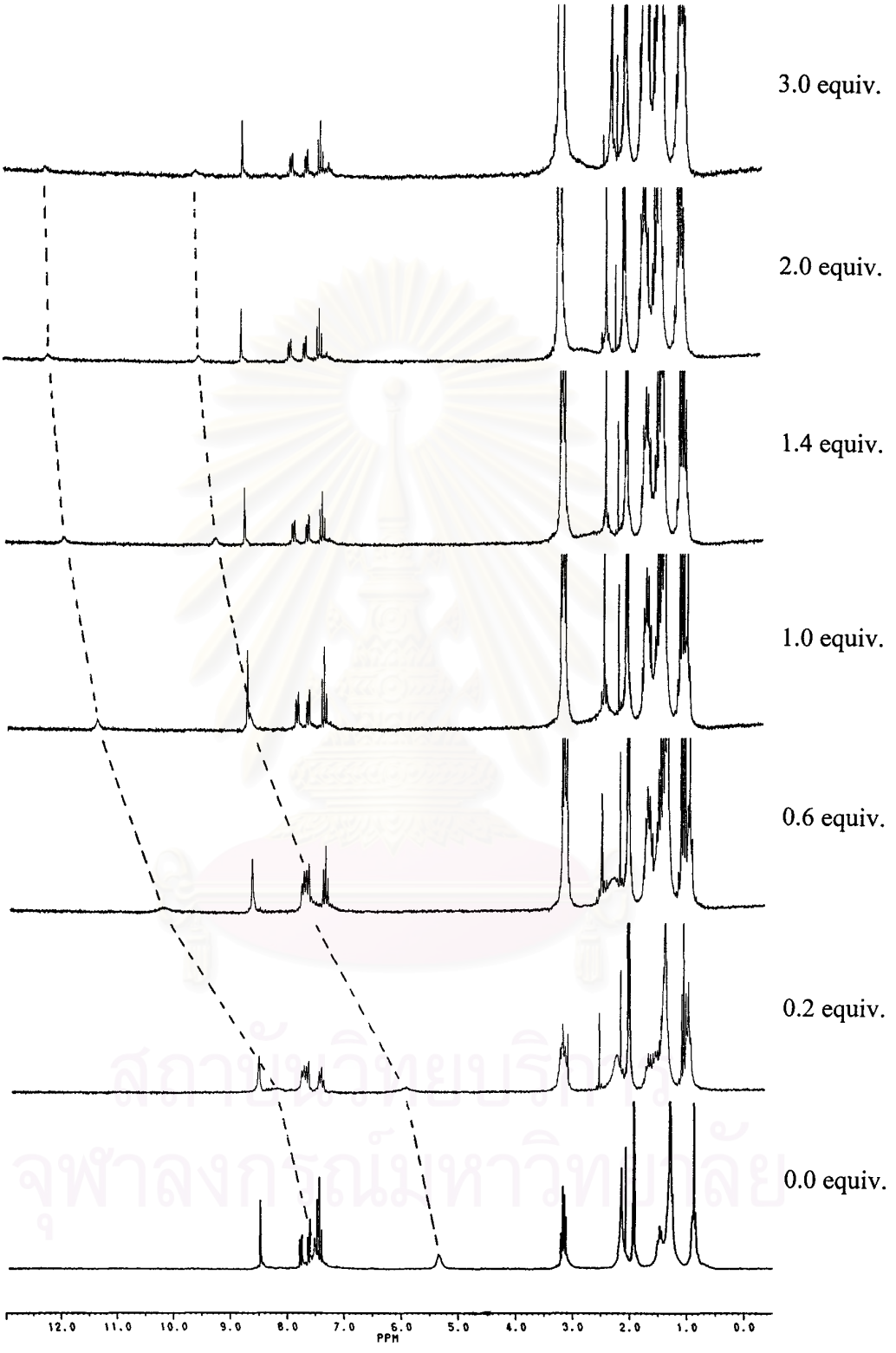



**Figure B.20** $^{1}$H-NMR spectra of **2b** (after irradiation) and succinate in $CD_3CN$ with 200 MHz.

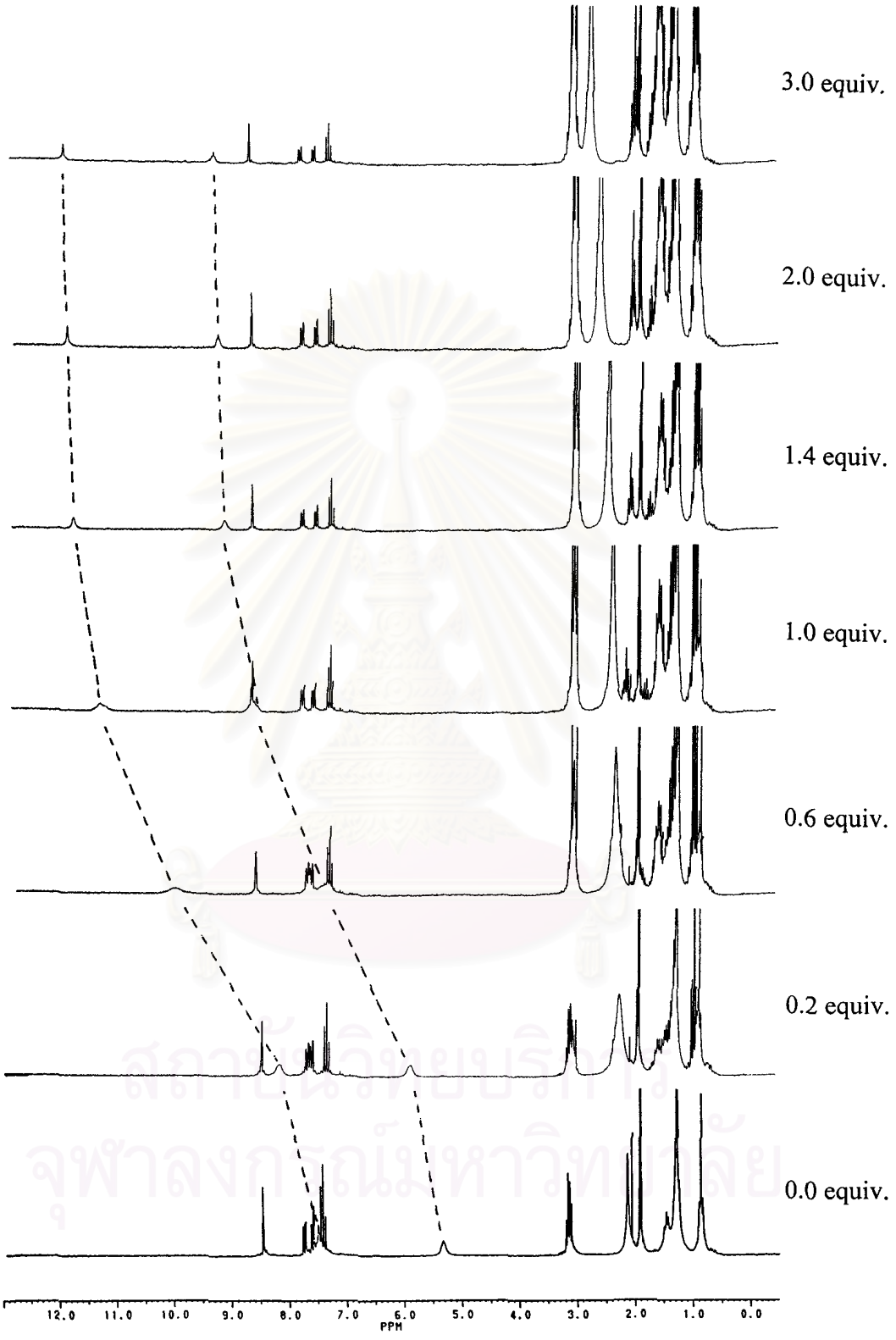



**Figure B.21** $^{1}$H-NMR spectra of **2b** (after irradiation) and glutarate in $CD_3CN$ with 200 MHz.

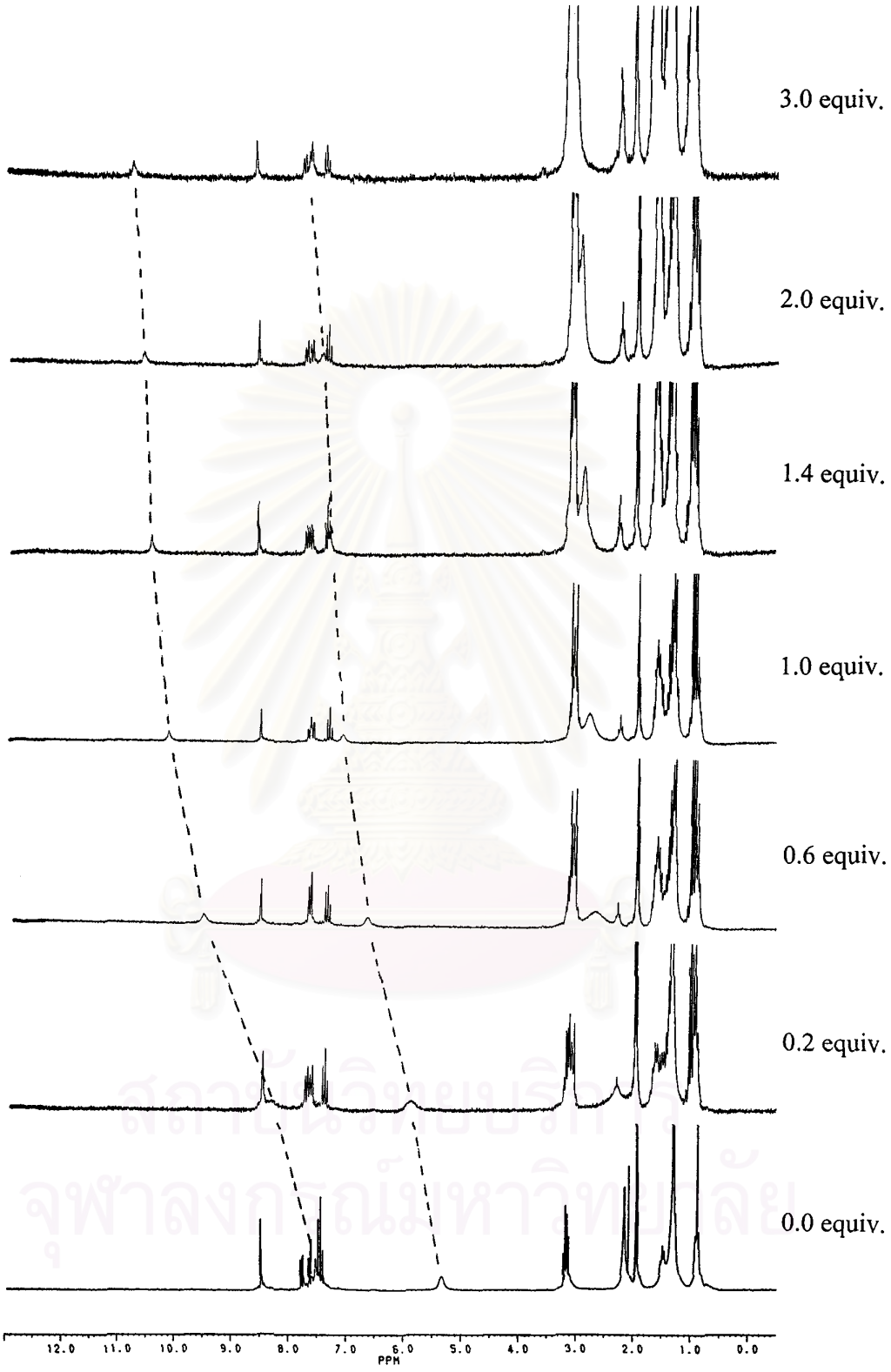



**Figure B.22** $^{1}$H-NMR spectra of **2b** (after irradiation) and adipate in $CD_3CN$ with 200 MHz.

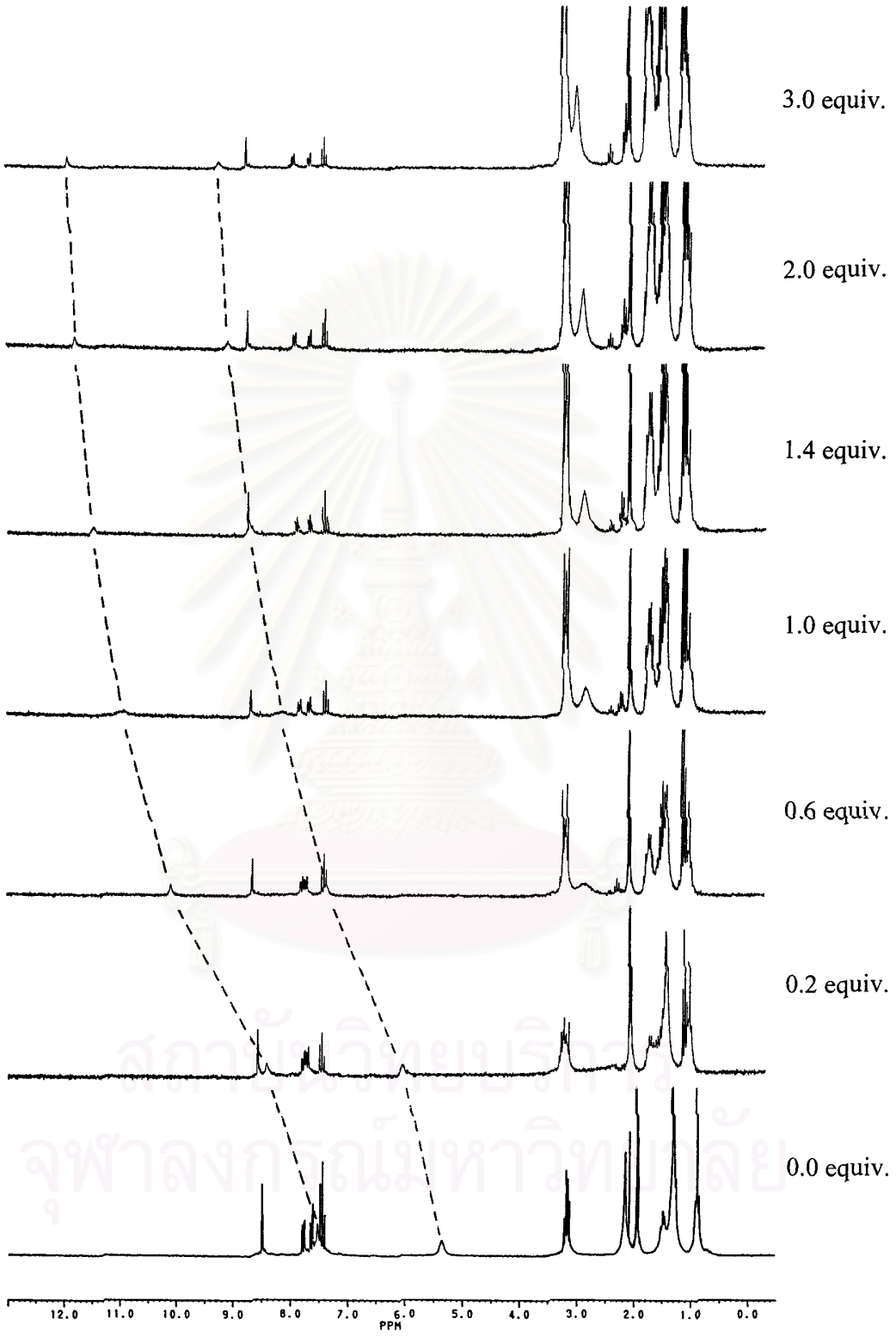



**Figure B.23** $^{1}$H-NMR spectra of **2b** (after irradiation) and pimelate in $CD_3CN$ with 200 MHz.

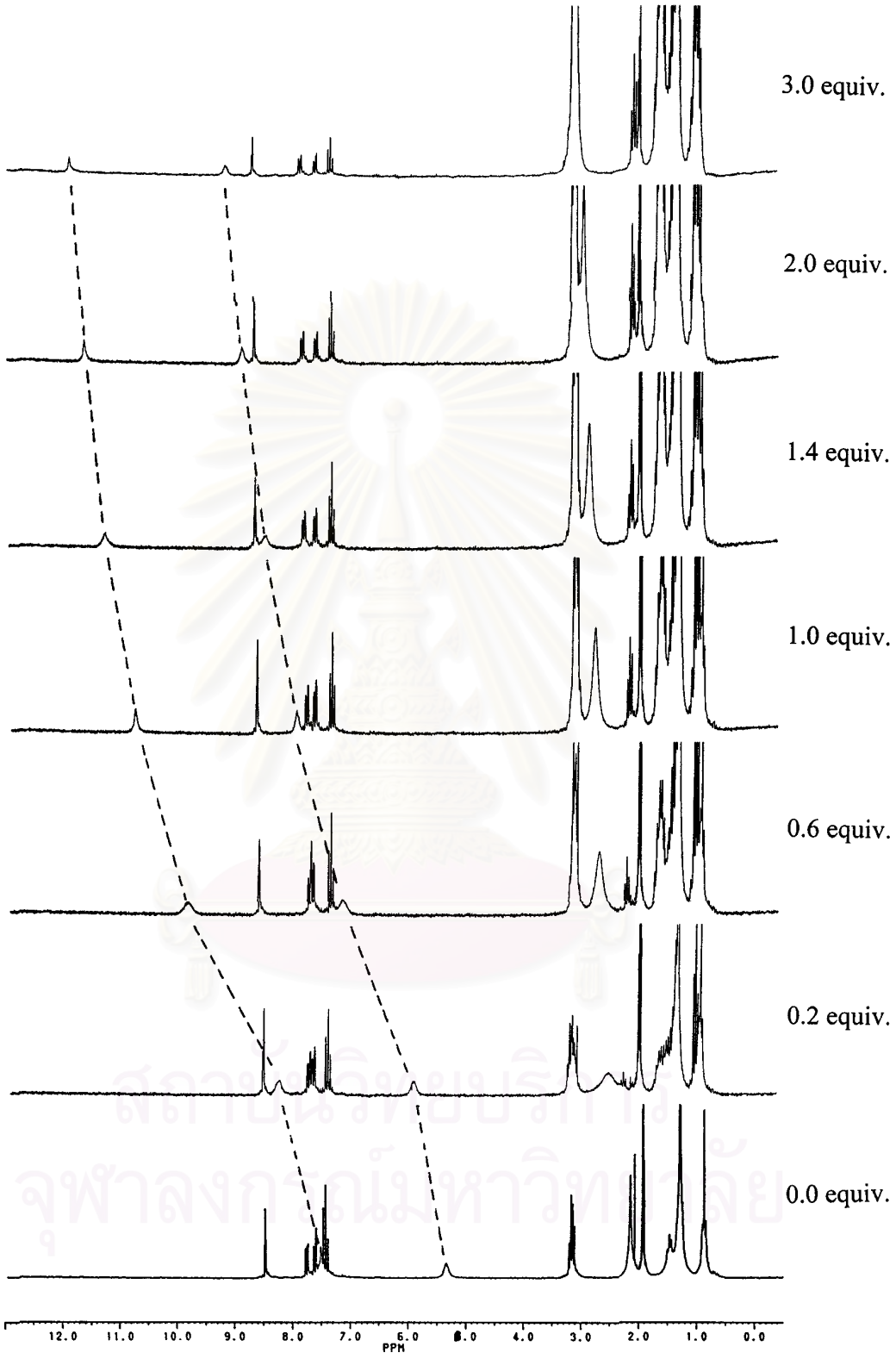



**Figure B.24** $^{1}$H-NMR spectra of **2b** (after irradiation) and azelate in $CD_3CN$ with 200 MHz.

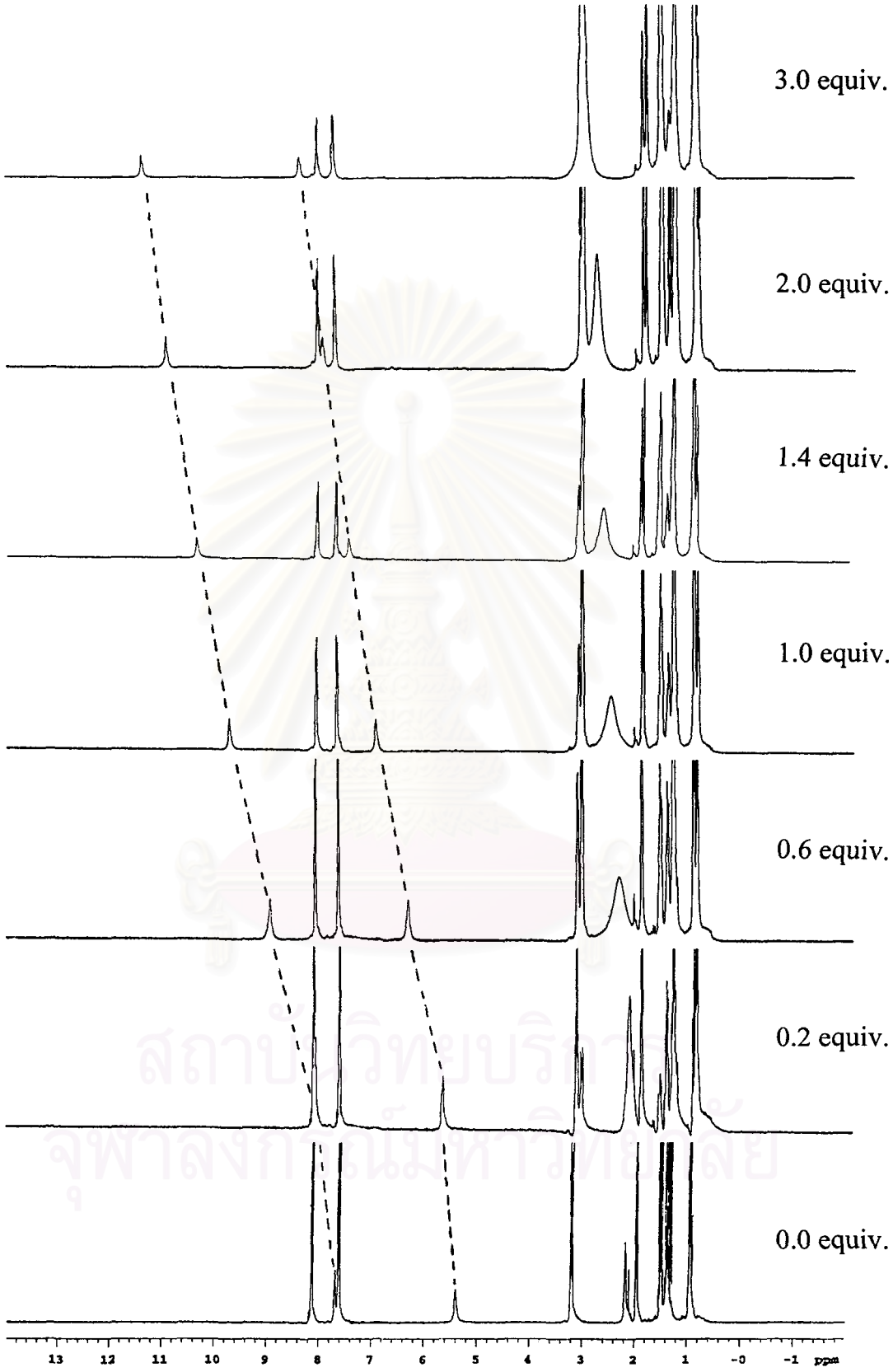



**Figure B.25** $^{1}$H-NMR spectra of **5a** (after irradiation) and acetate in $CD_3CN$ with 400 MHz.

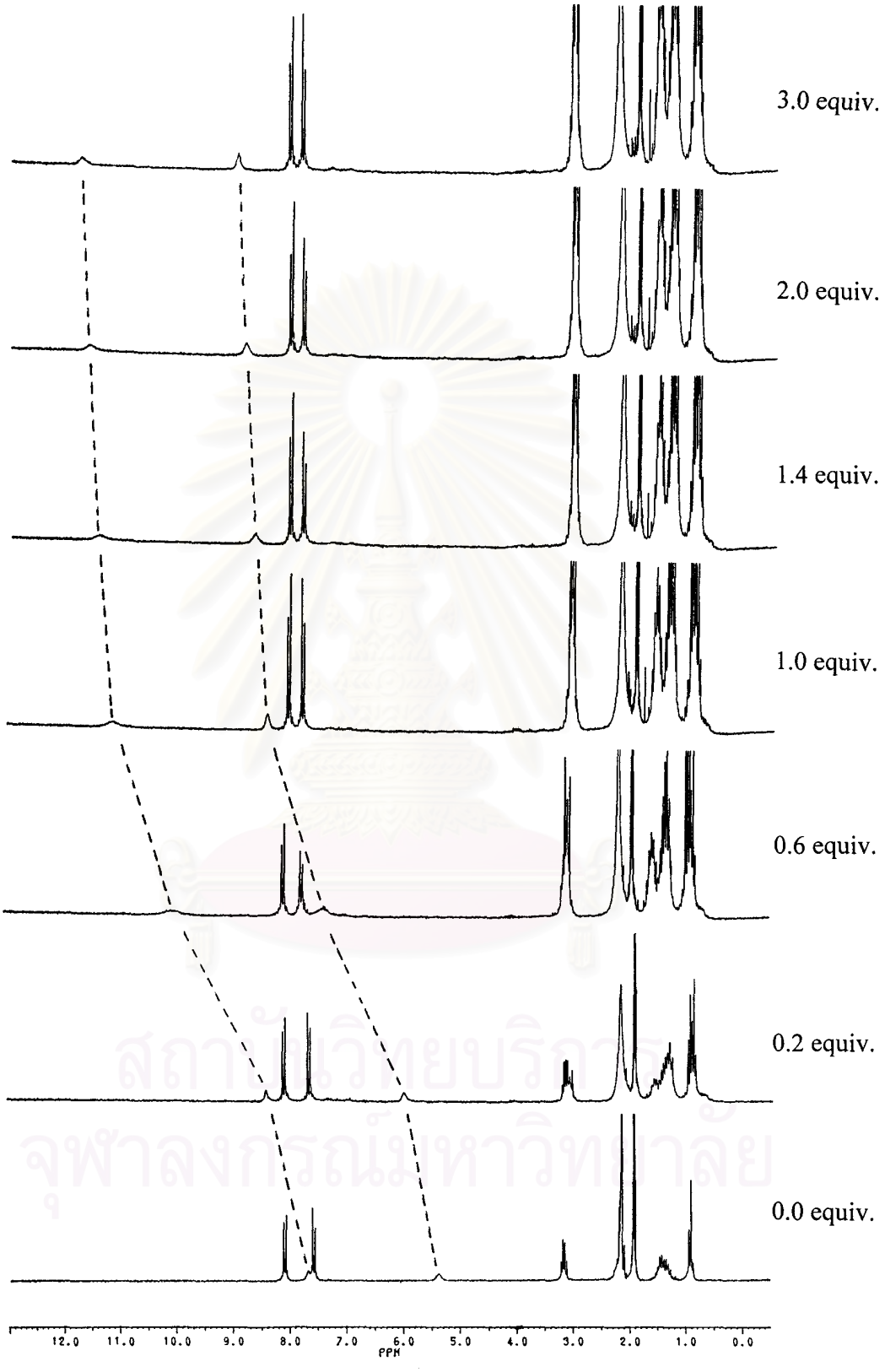



**Figure B.26** $^{1}$H-NMR spectra of **5a** (after irradiation) and oxalate in $CD_3CN$ with 200 MHz.

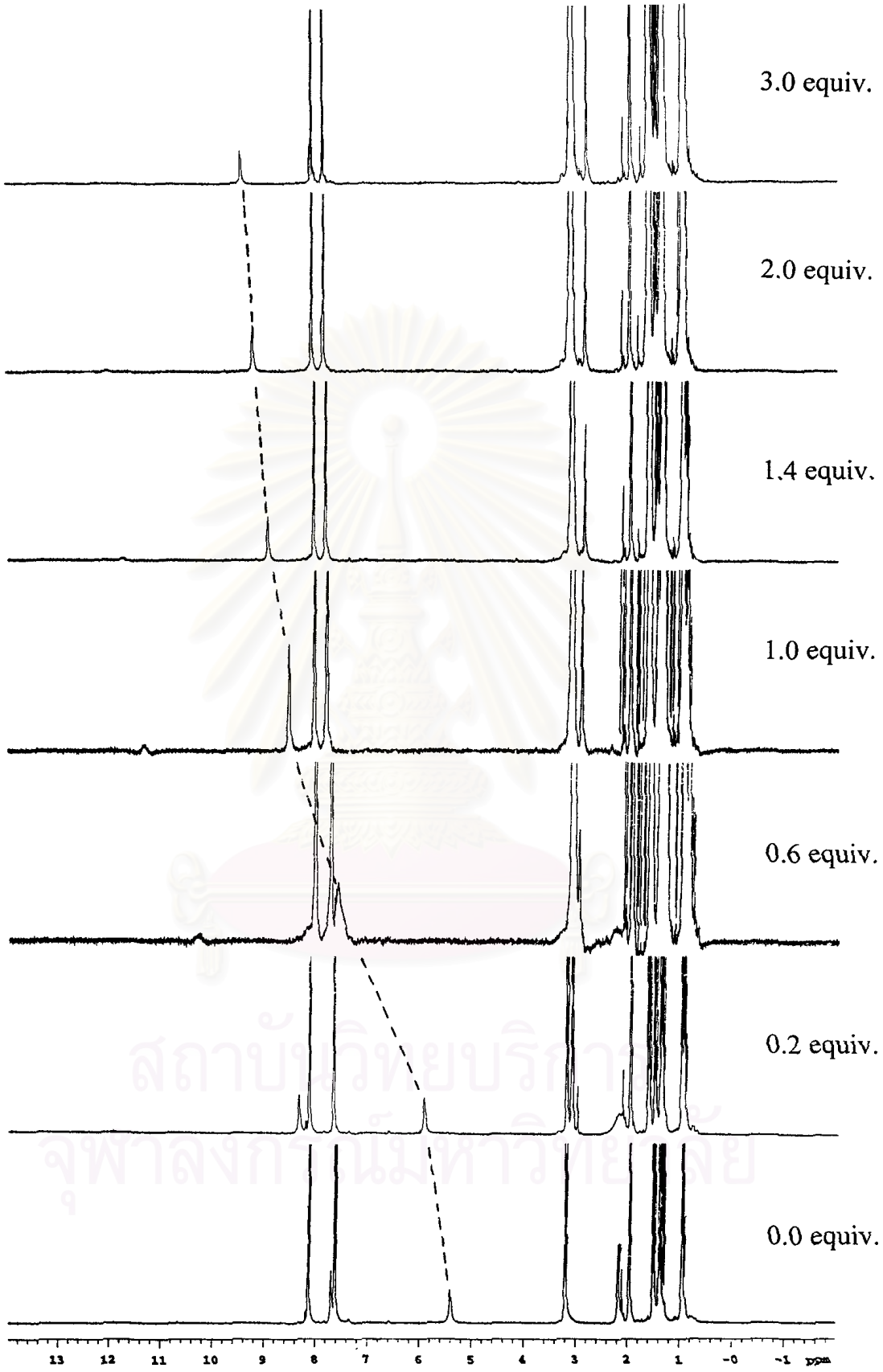



**Figure B.27** $^{1}$H-NMR spectra of **5a** (after irradiation) and malonate in $CD_3CN$ with 400 MHz.

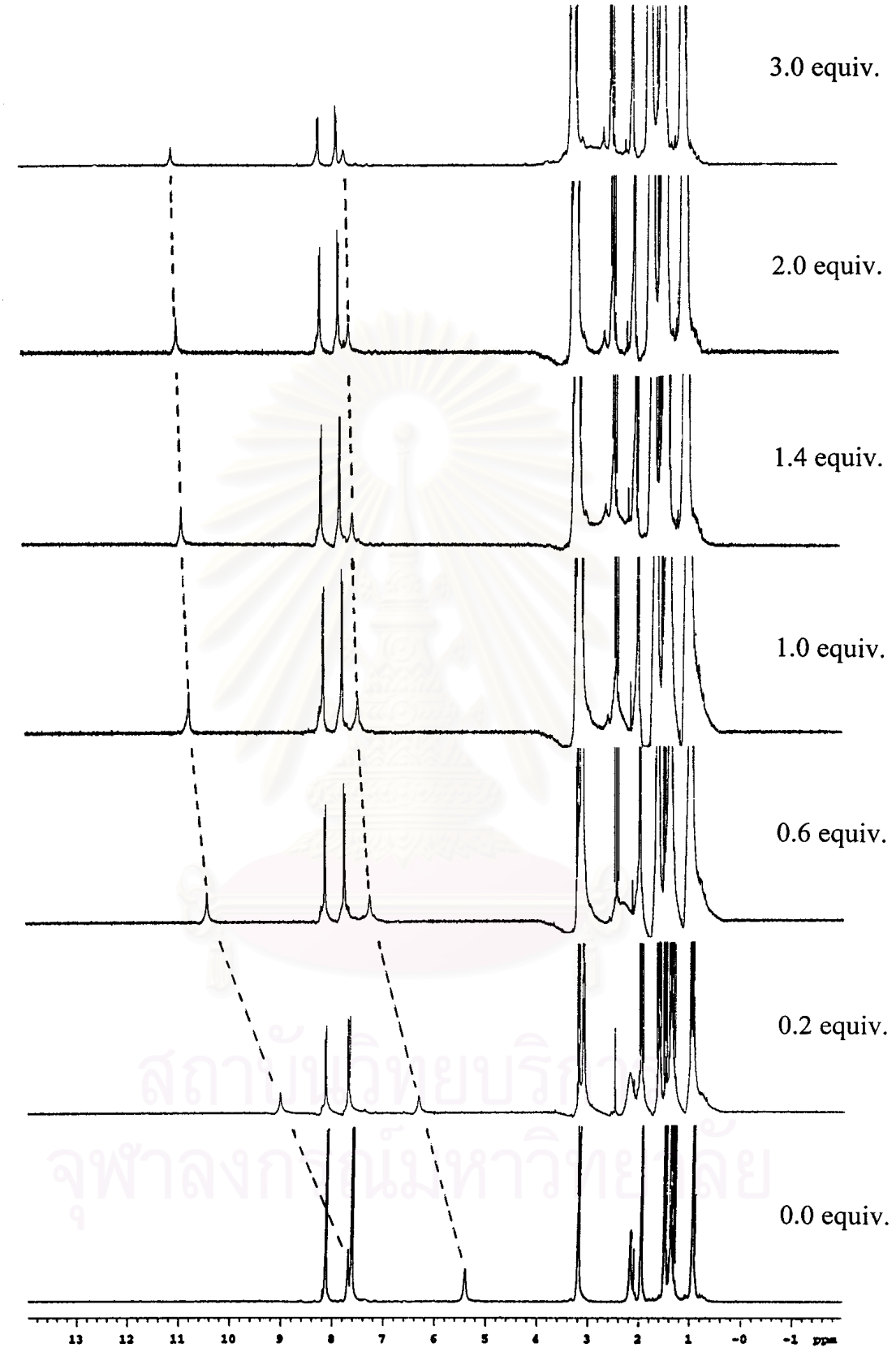



**Figure B.28** $^{1}$H-NMR spectra of **5a** (after irradiation) and succinate in $CD_3CN$ with 400 MHz.

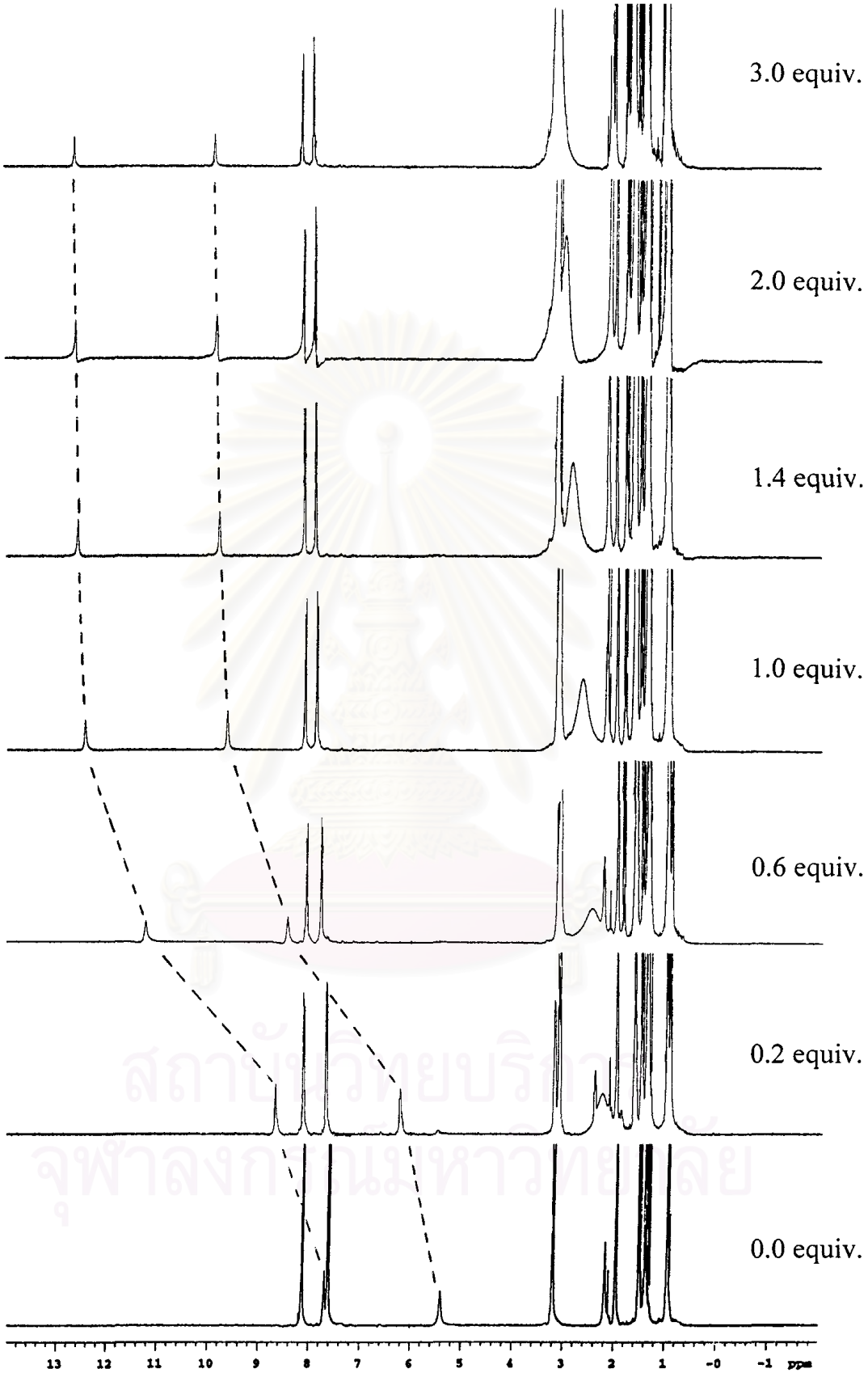



**Figure B.29** $^{1}$H-NMR spectra of **5a** (after irradiation) and glutarate in $CD_3CN$ with 400 MHz.

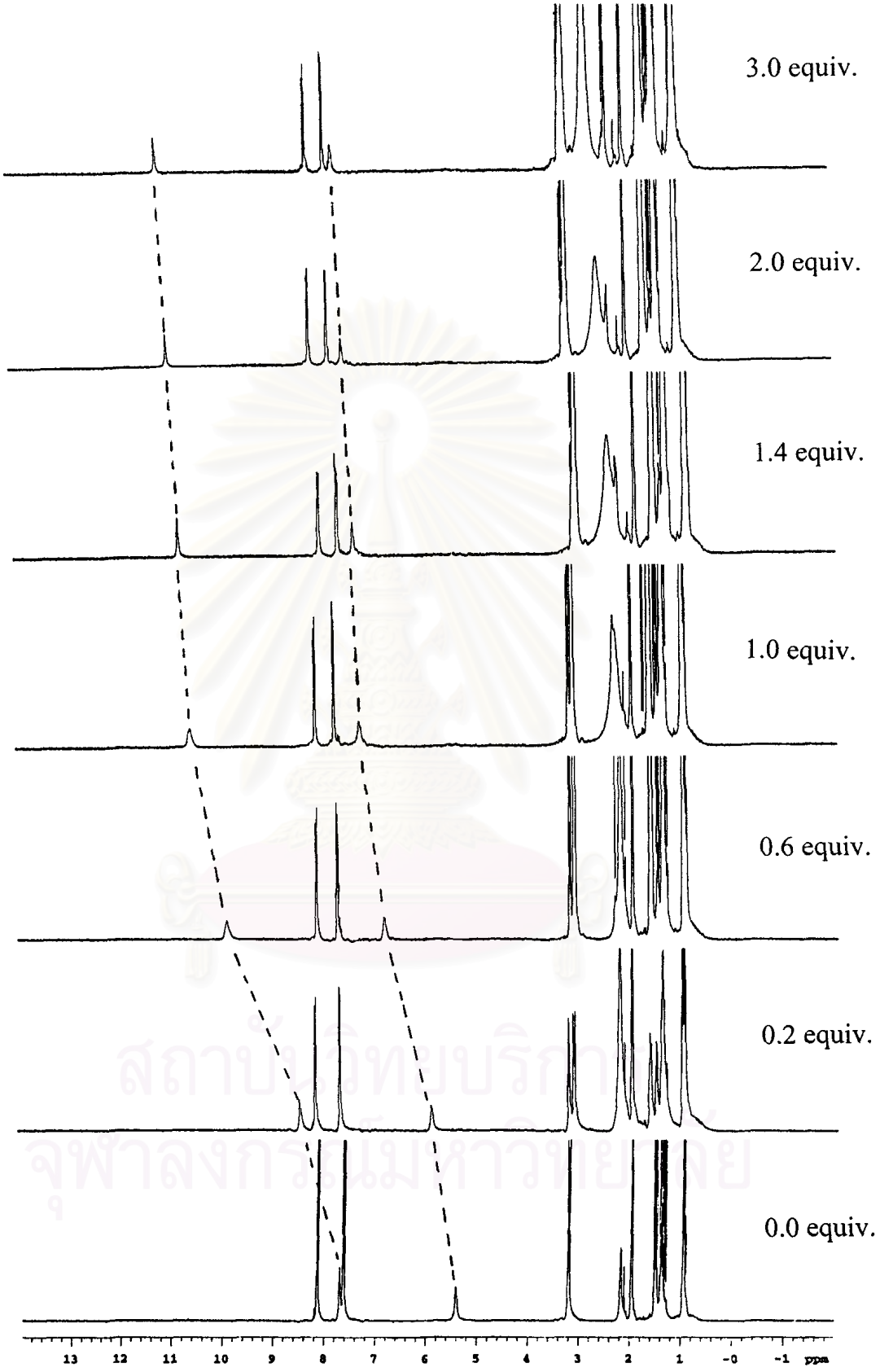



**Figure B.30** $^{1}$H-NMR spectra of **5a** (after irradiation) and adipate in $CD_3CN$ with 400 MHz.

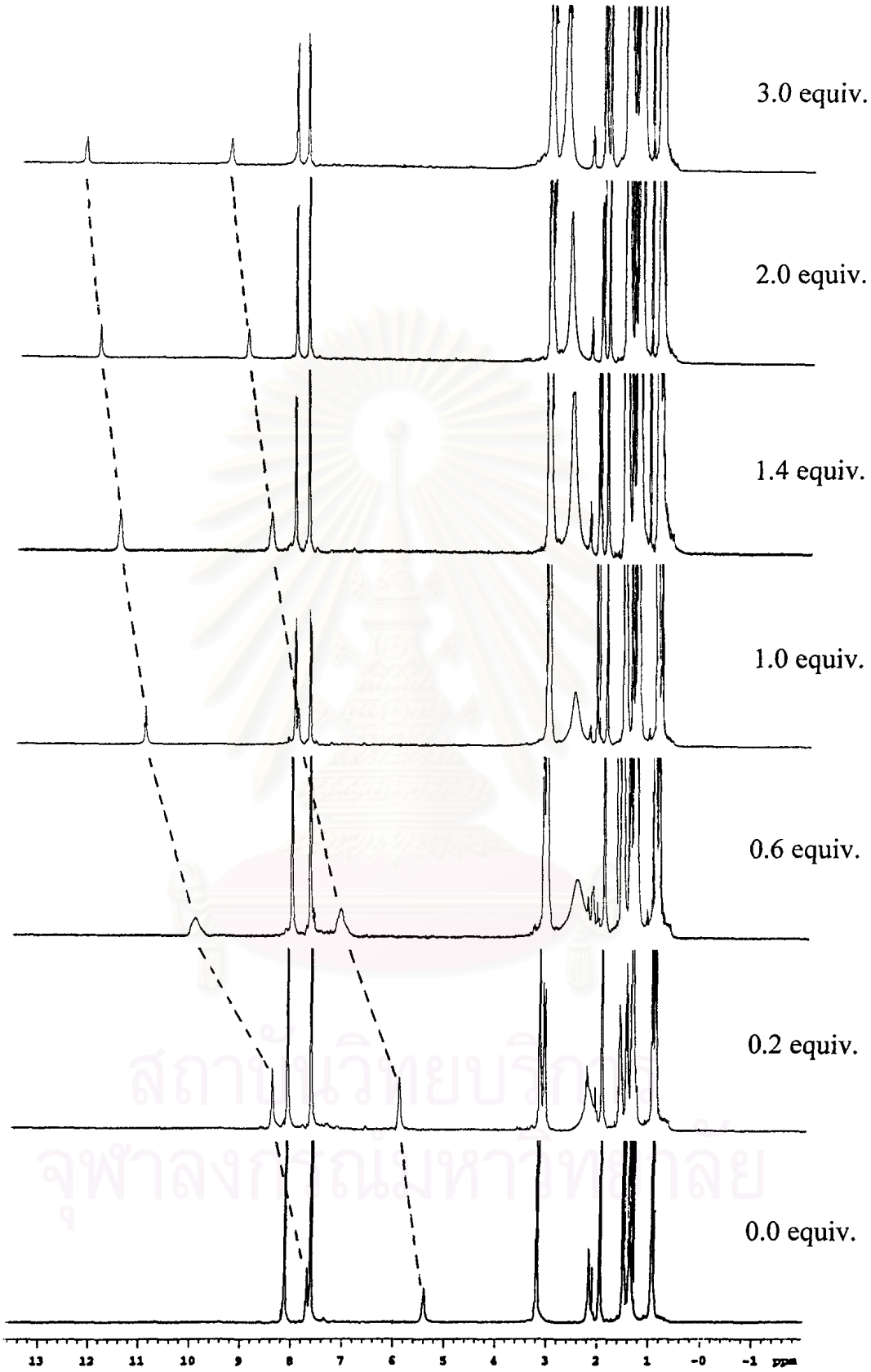



**Figure B.31** $^{1}$H-NMR spectra of **5a** (after irradiation) and pimelate in $CD_3CN$ with 400 MHz.

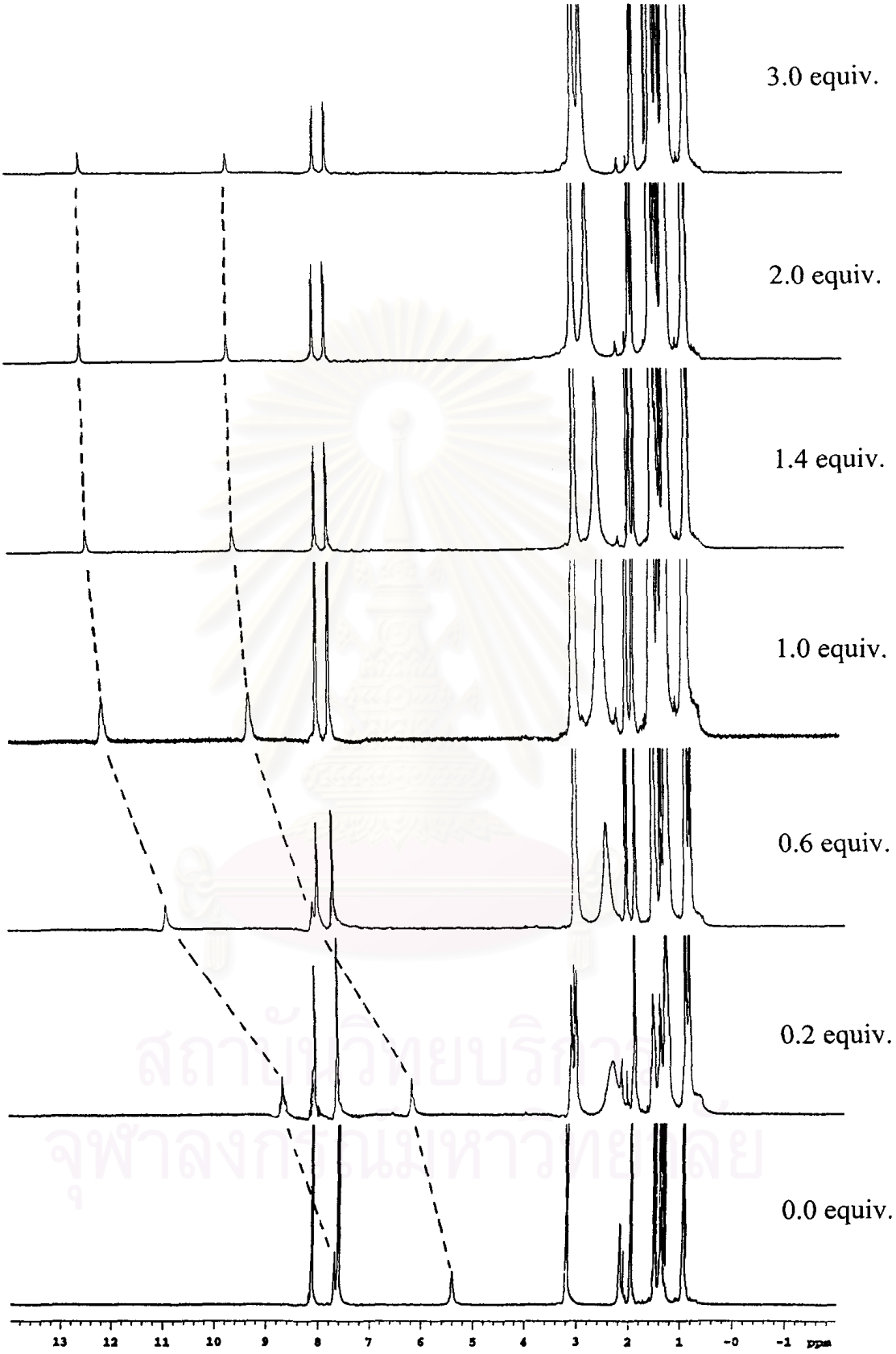



**Figure B.32** $^{1}$H-NMR spectra of **5a** (after irradiation) and azelate in $CD_3CN$ with 400 MHz.

# APPENDIX C

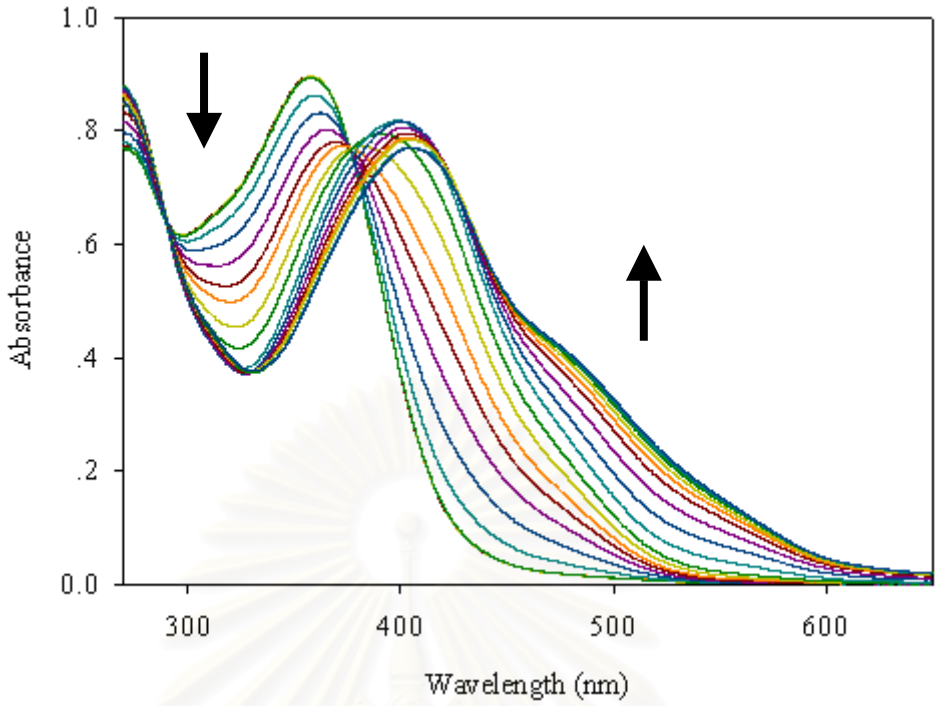



**Figure C.1** UV-vis titration spectra of compound **2d** with acetate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [acetate] = 0-30 equiv.).

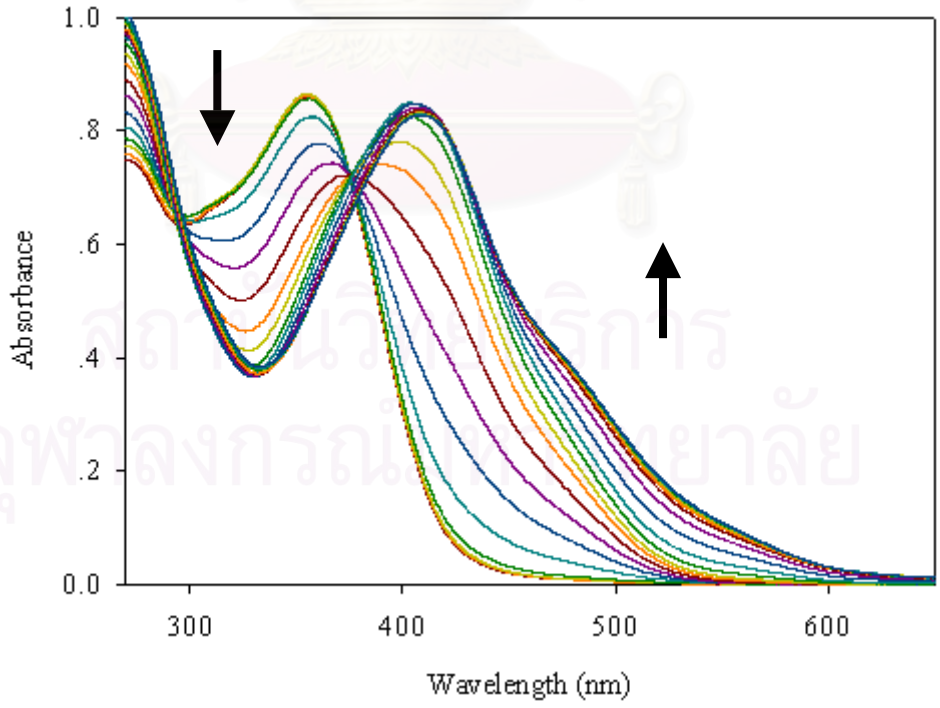



**Figure C.2** UV-vis titration spectra of compound **2d** with oxalate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [oxalate] = 0-18 equiv.).

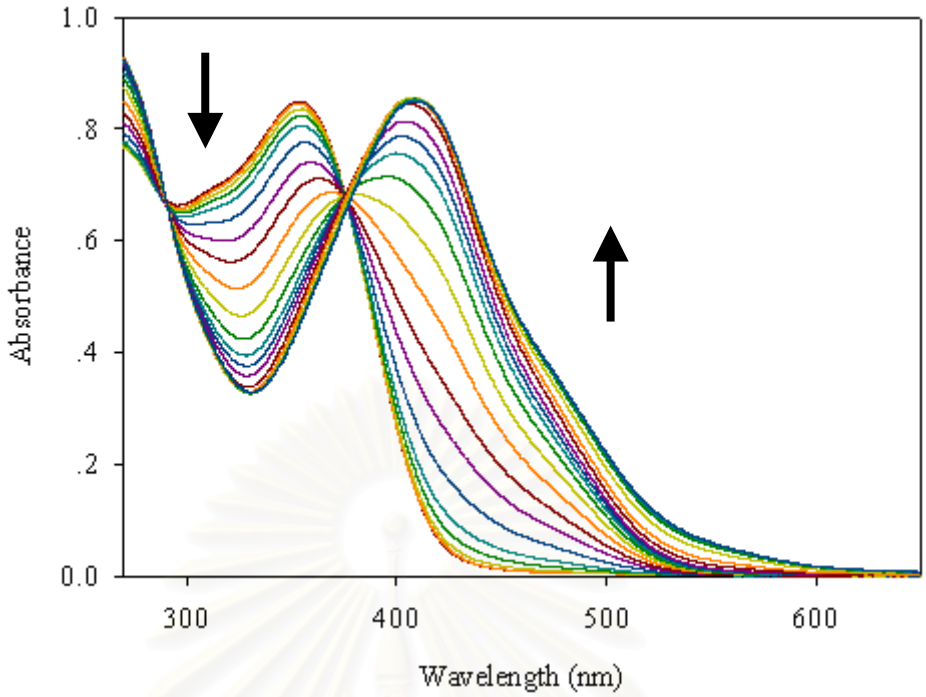



**Figure C.3** UV-vis titration spectra of compound **2d** with malonate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [malonate] = 0-17 equiv.).

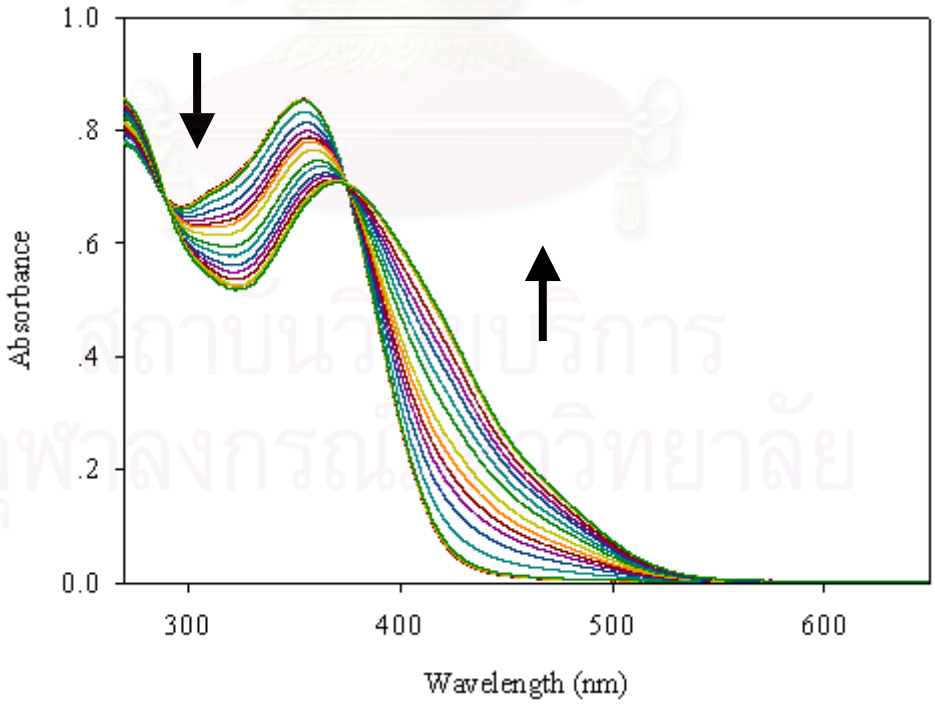



**Figure C.4** UV-vis titration spectra of compound **2d** with succinate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [succinate] = 0-17 equiv.).

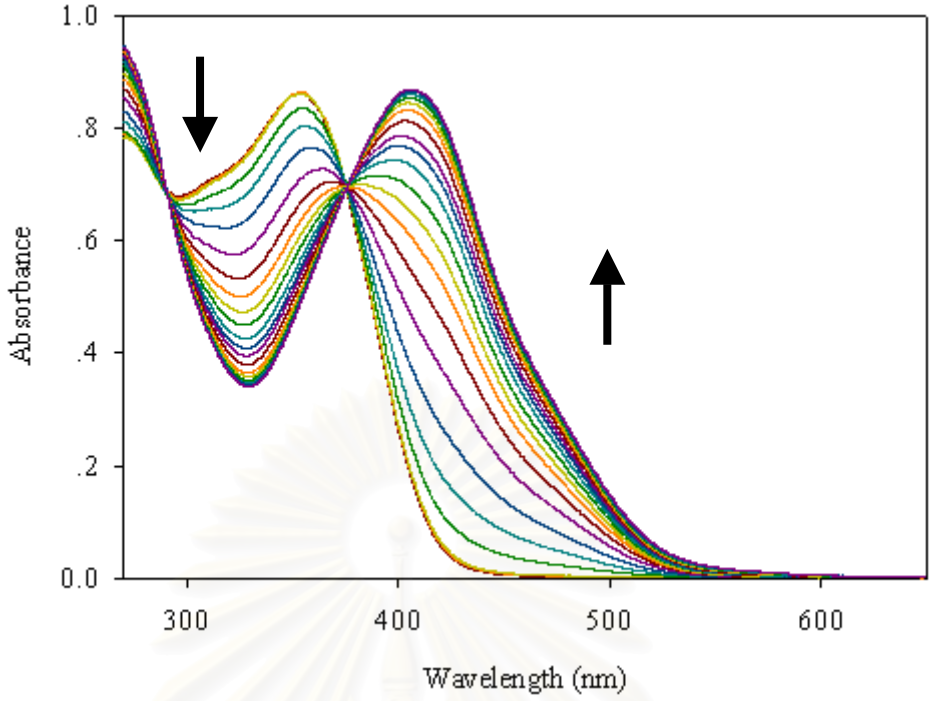



**Figure C.5** UV-vis titration spectra of compound **2d** with glutarate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [glutarate] = 0-8 equiv.).

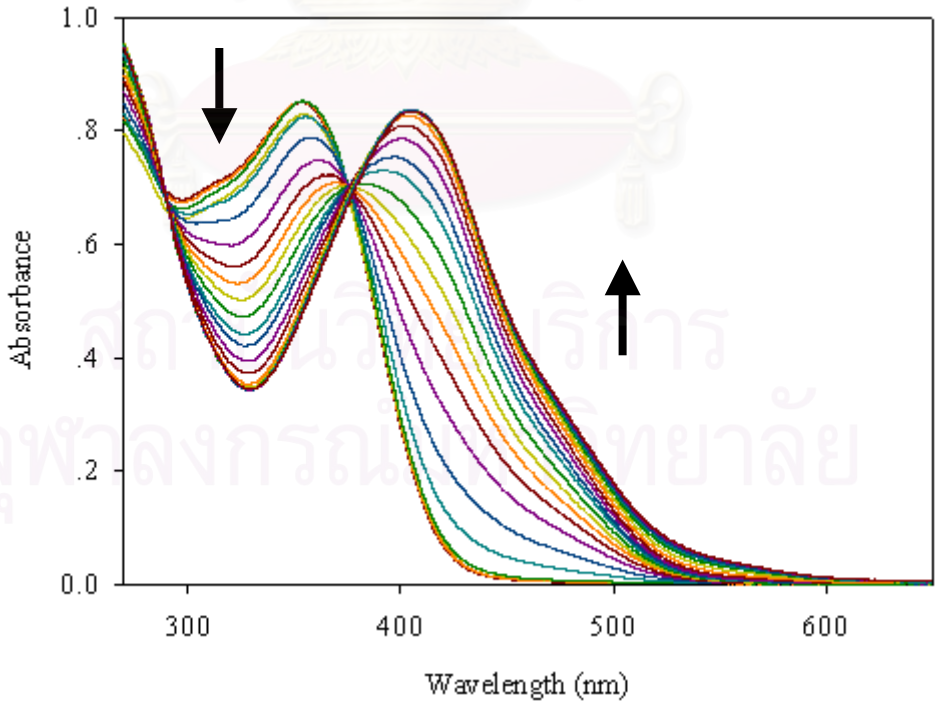



**Figure C.6** UV-vis titration spectra of compound **2d** with adipate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [adipate] = 0-30 equiv.).

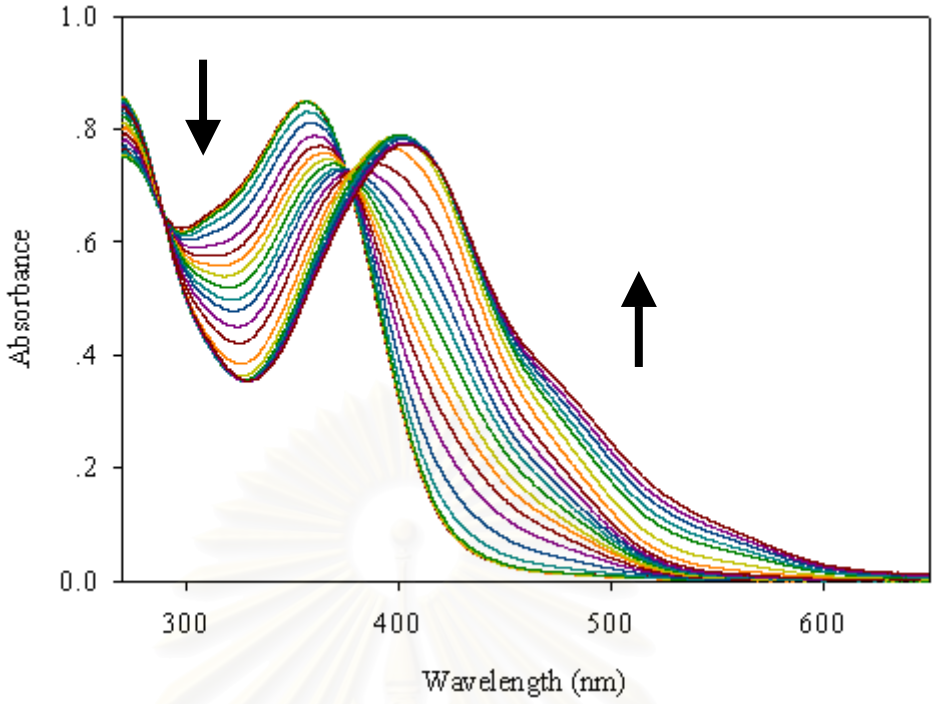



**Figure C.7** UV-vis titration spectra of compound **2d** with pimelate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [pimelate] = 0-12 equiv.).

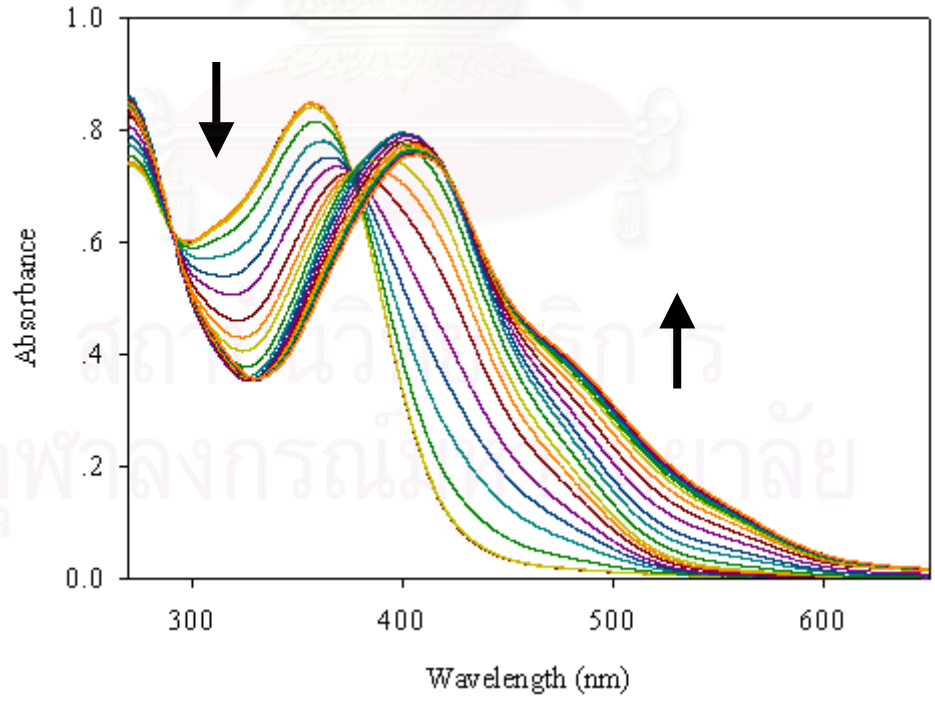



**Figure C.8** UV-vis titration spectra of compound **2d** with azelate in DMSO ([**2d**] = 2.5 x $10^{-5}$ M, [azelate] = 0-9 equiv.).

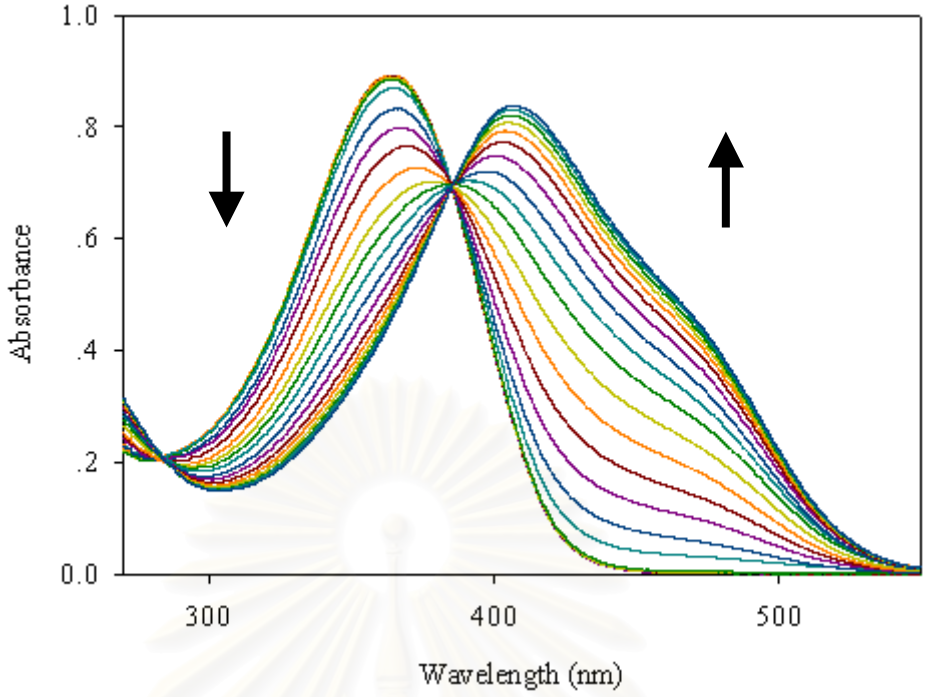



**Figure C.9** UV-vis titration spectra of compound **5d** with acetate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [acetate] = 0-40 equiv.).

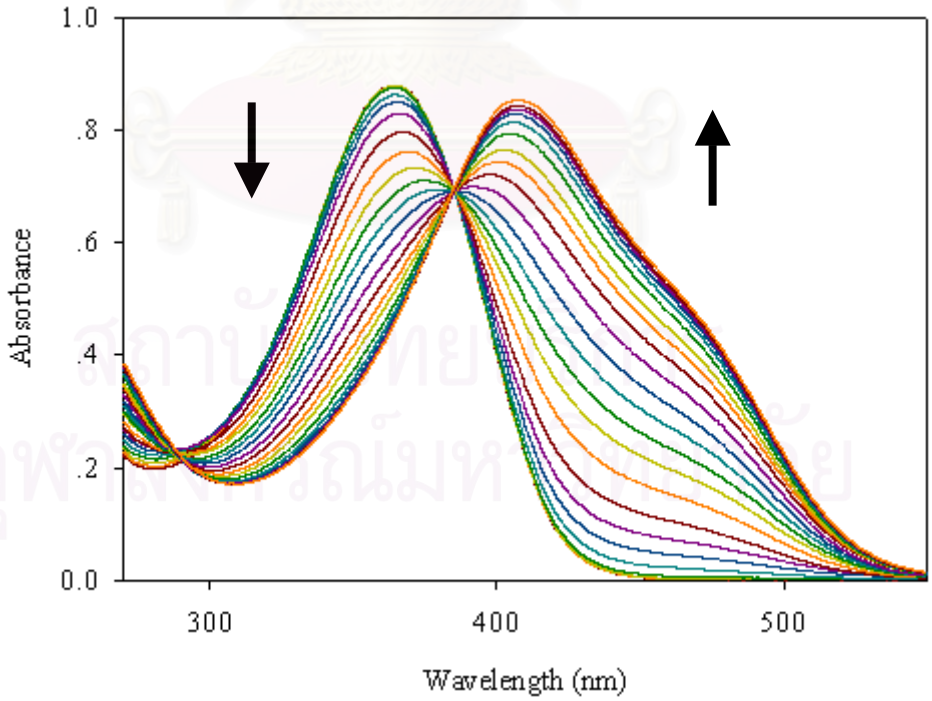



**Figure C.10** UV-vis titration spectra of compound **5d** with oxalate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [oxalate] = 0-20 equiv.).

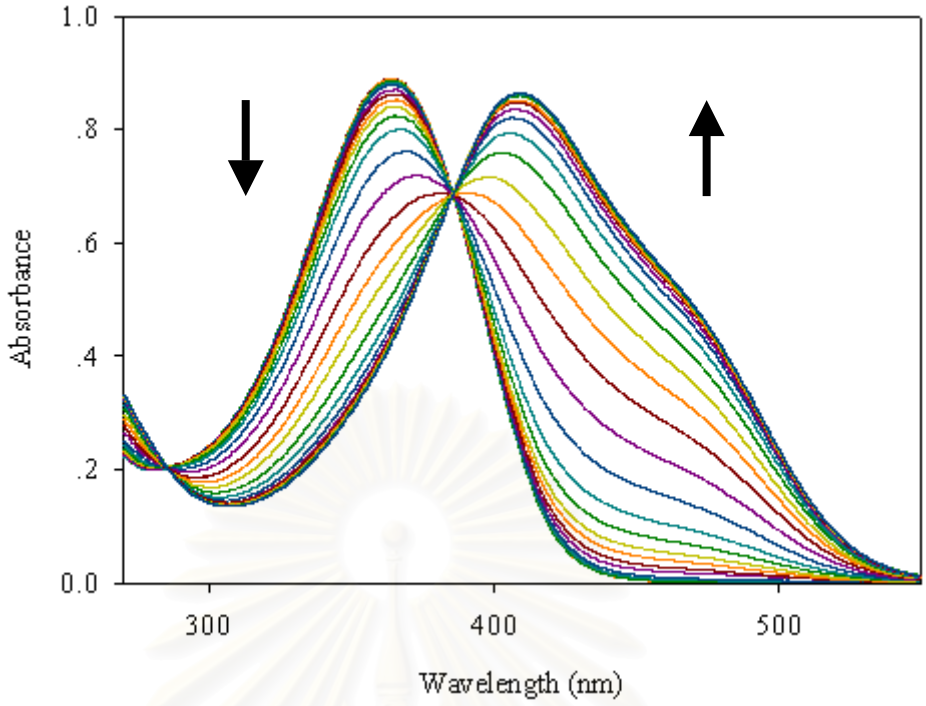



**Figure C.11** UV-vis titration spectra of compound **5d** with malonate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [malonate] = 0-15 equiv.).

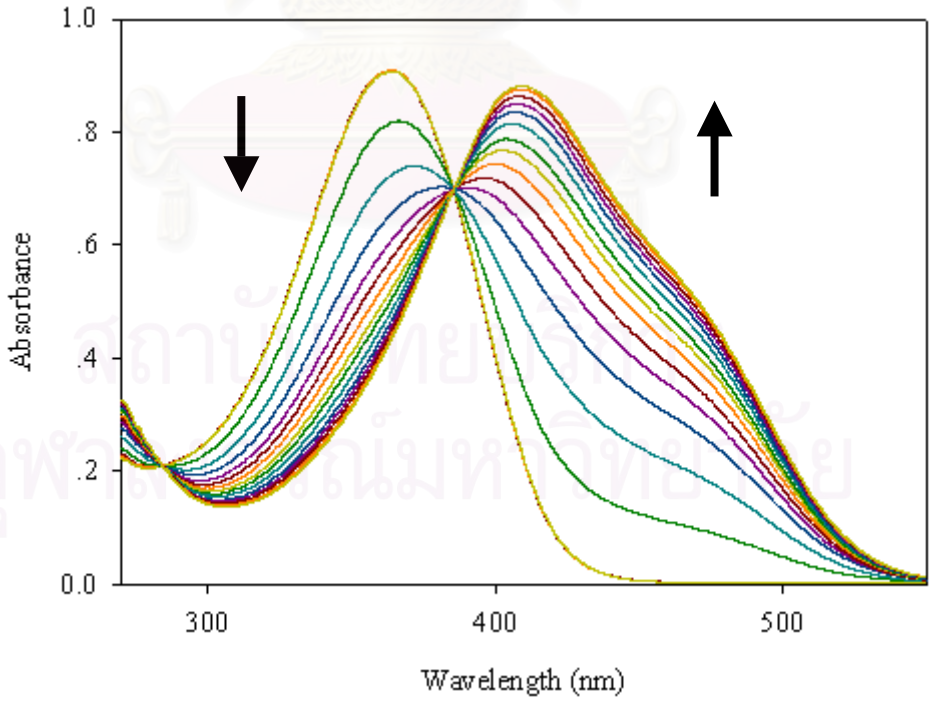



**Figure C.12** UV-vis titration spectra of compound **5d** with succinate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [succinate] = 0-10 equiv.).

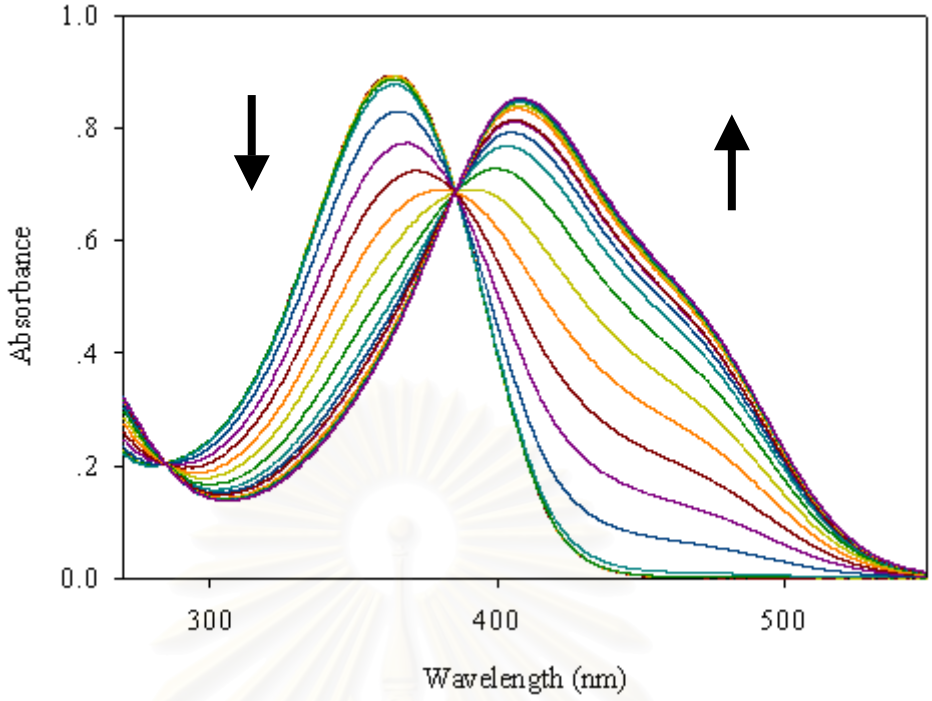



**Figure C.13** UV-vis titration spectra of compound **5d** with glutarate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [glutarate] = 0-8 equiv.).

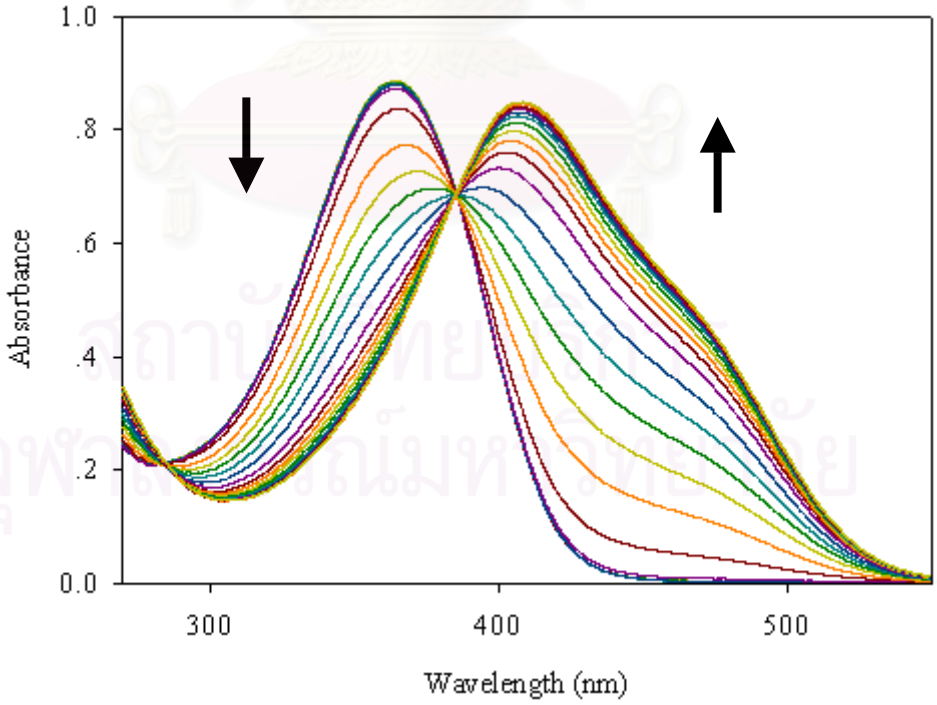



**Figure C.14** UV-vis titration spectra of compound **5d** with adipate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [adipate] = 0-20 equiv.).

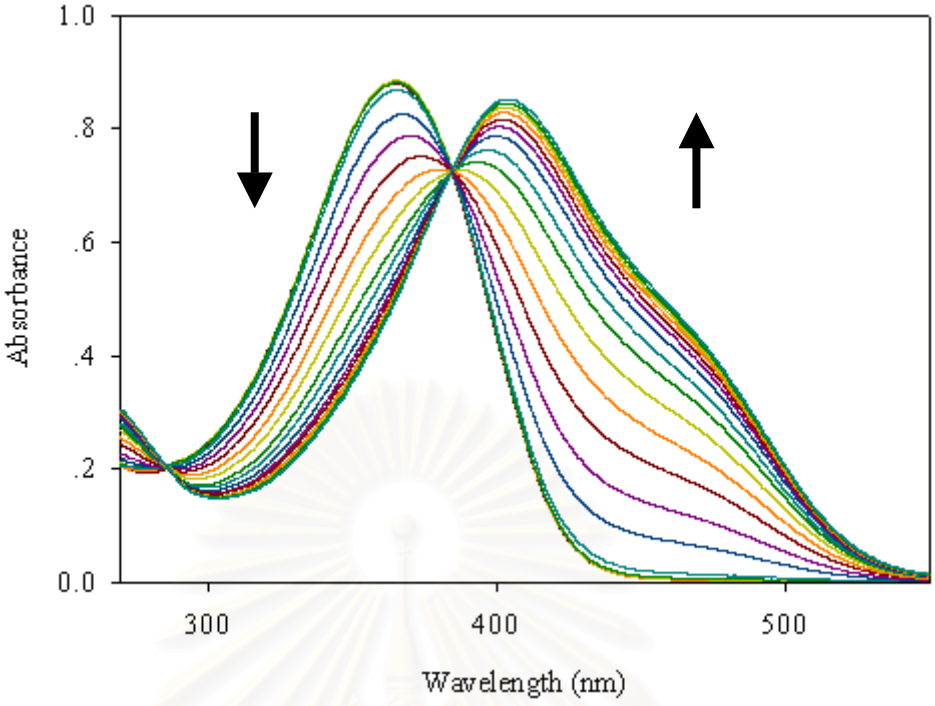



**Figure C.15** UV-vis titration spectra of compound **5d** with pimelate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [pimelate] = 0-13 equiv.).

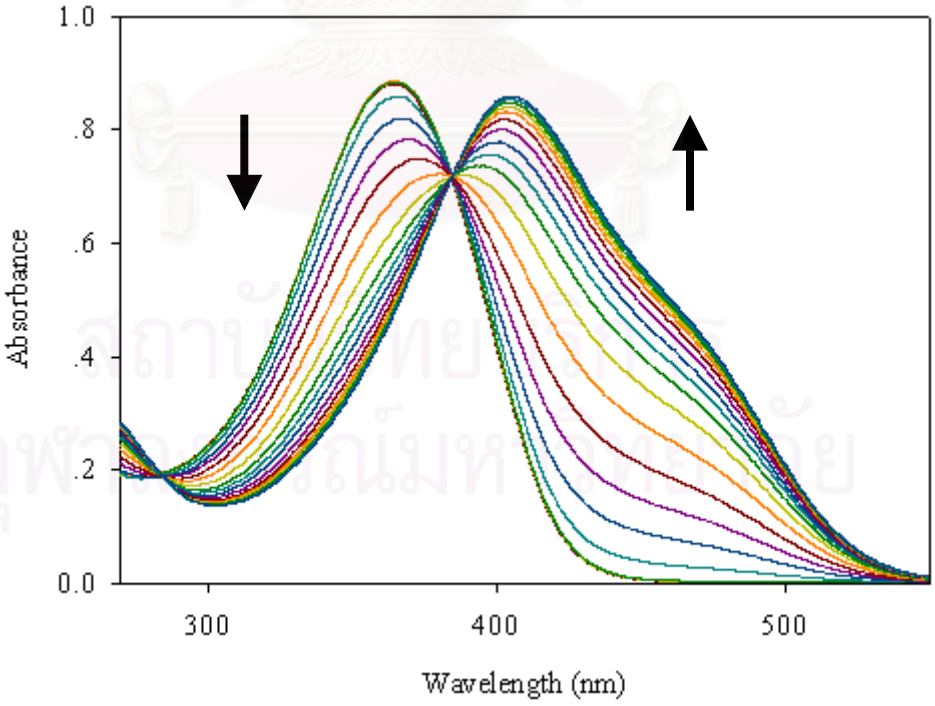



**Figure C.16** UV-vis titration spectra of compound **5d** with azelate in DMSO ([**5d**] = 1.5 x $10^{-5}$ M, [azelate] = 0-8 equiv.).

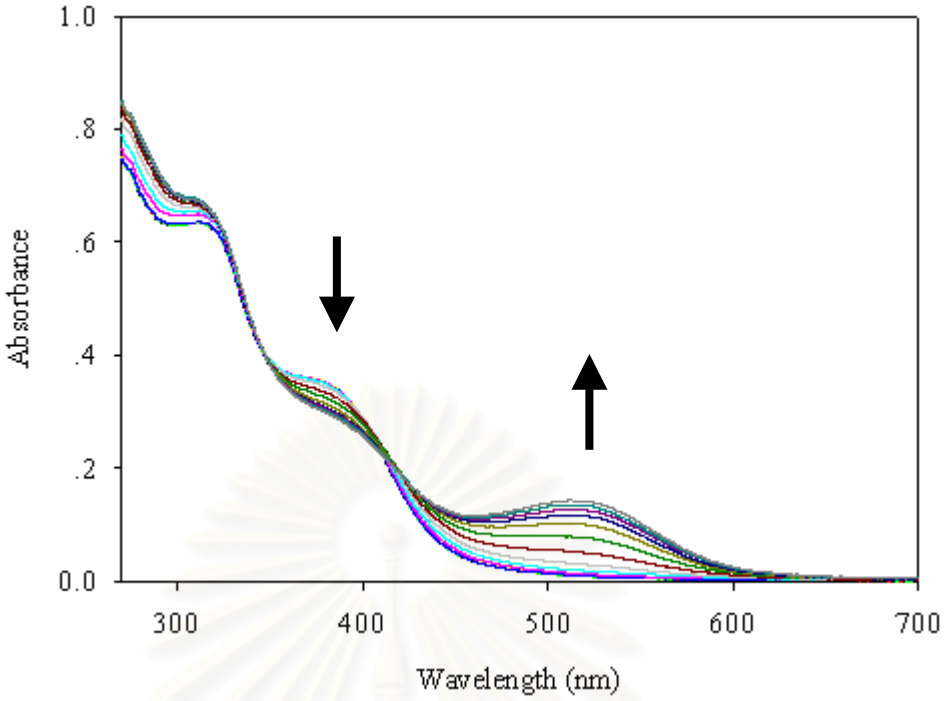



**Figure C.17** UV-vis titration spectra of the **2d** (after irradiation) with acetate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [acetate] = 0-70 equiv.).

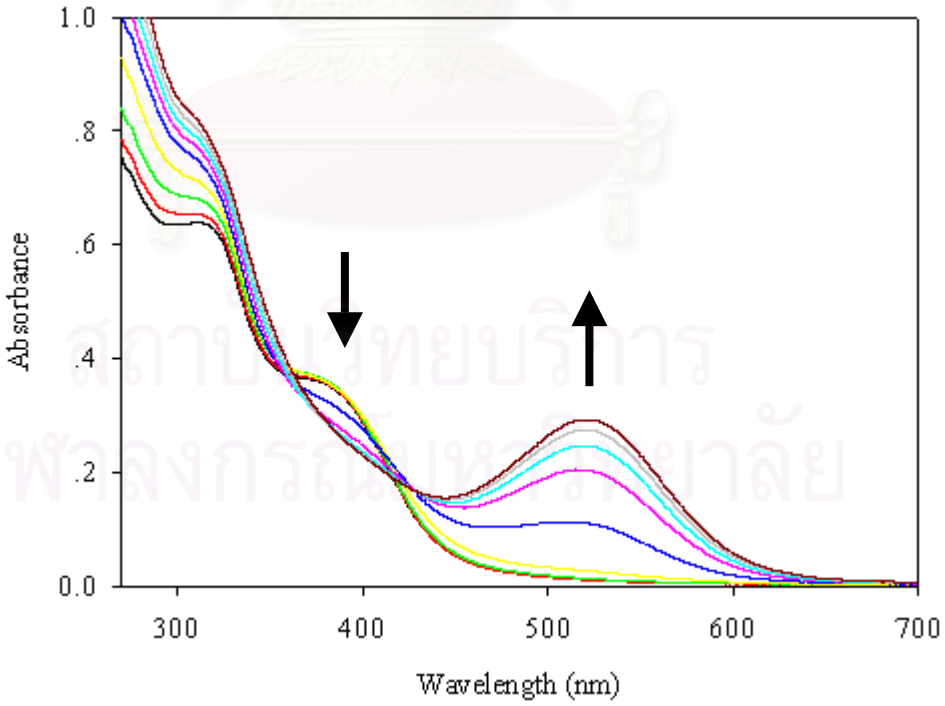



**Figure C.18** UV-vis titration spectra of the **2d** (after irradiation) with oxalate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [oxalate] = 0-40 equiv.).

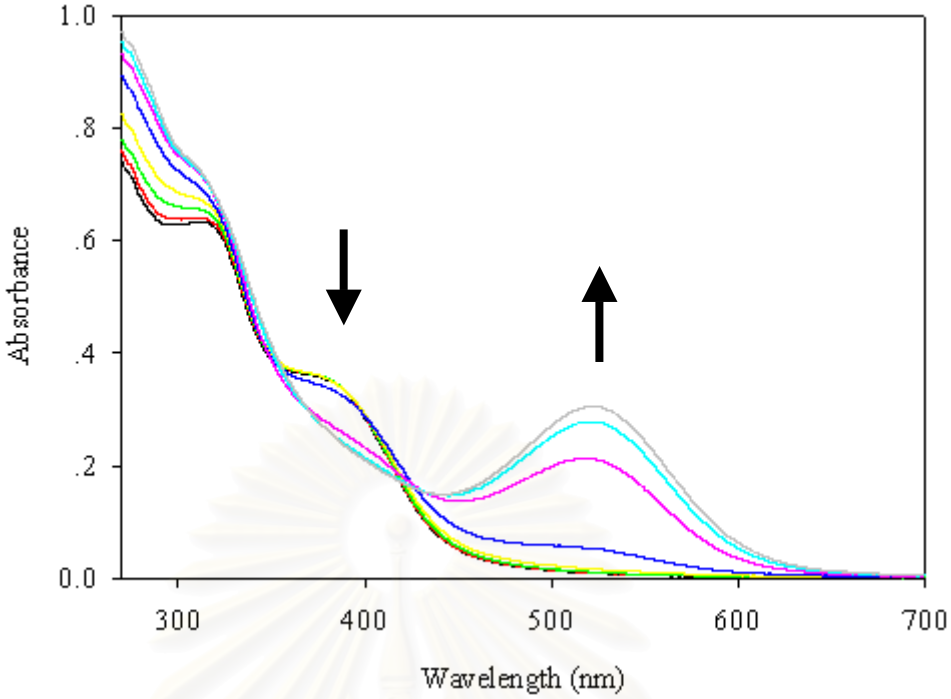



**Figure C.19** UV-vis titration spectra of the **2d** (after irradiation) with malonate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [malonate] = 0-35 equiv.).

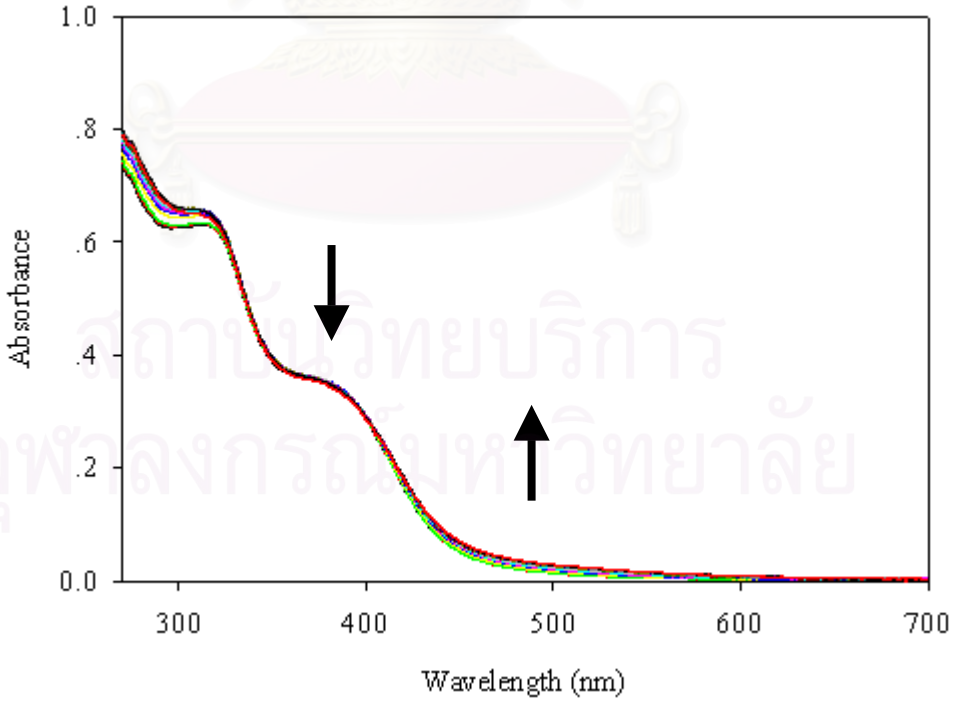



**Figure C.20** UV-vis titration spectra of the **2d** (after irradiation) with succinate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [succinate] = 0-80 equiv.).

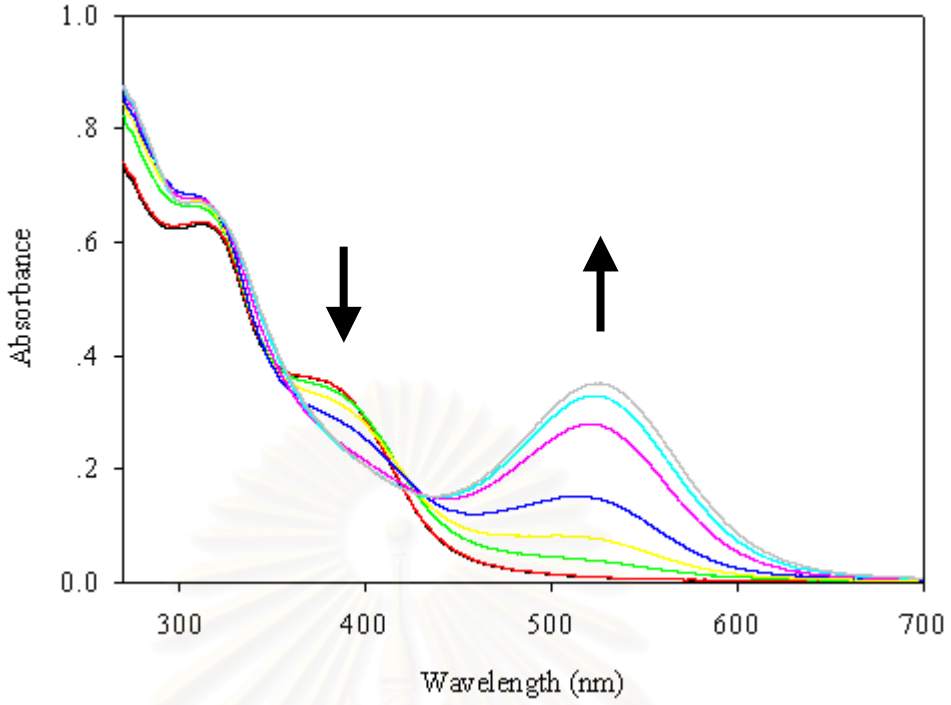



**Figure C.21** UV-vis titration spectra of the **2d** (after irradiation) with glutarate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [glutarate] = 0-35 equiv.).

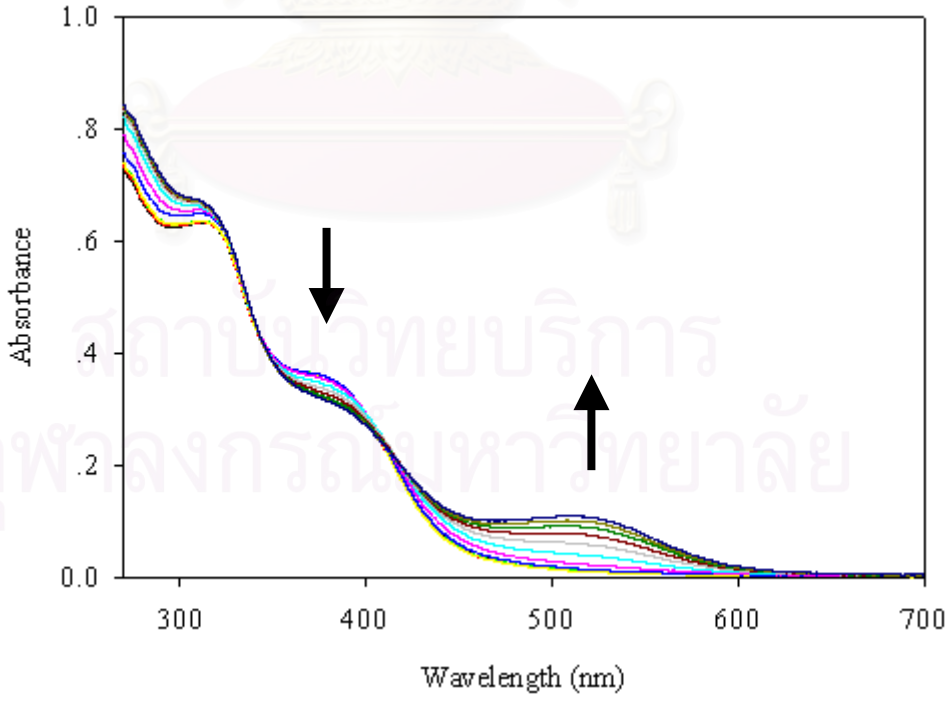



**Figure C.22** UV-vis titration spectra of **2d** (after irradiation) with adipate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [adipate] = 0-55 equiv.).

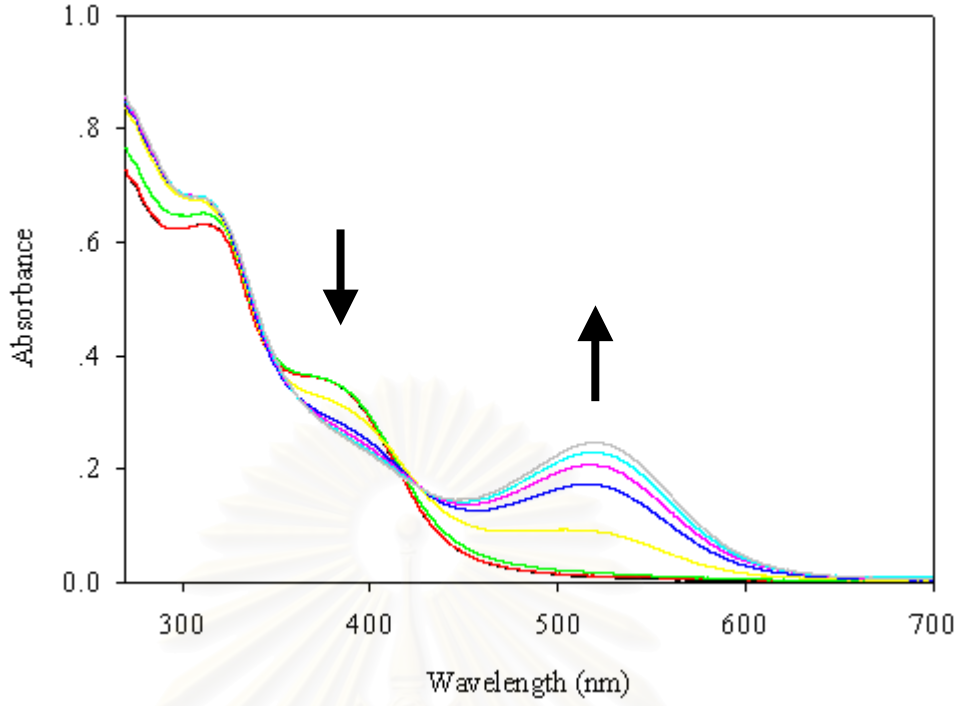



**Figure C.23** UV-vis titration spectra of **2d** (after irradiation) with pimelate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [pimelate] = 0-35 equiv.).

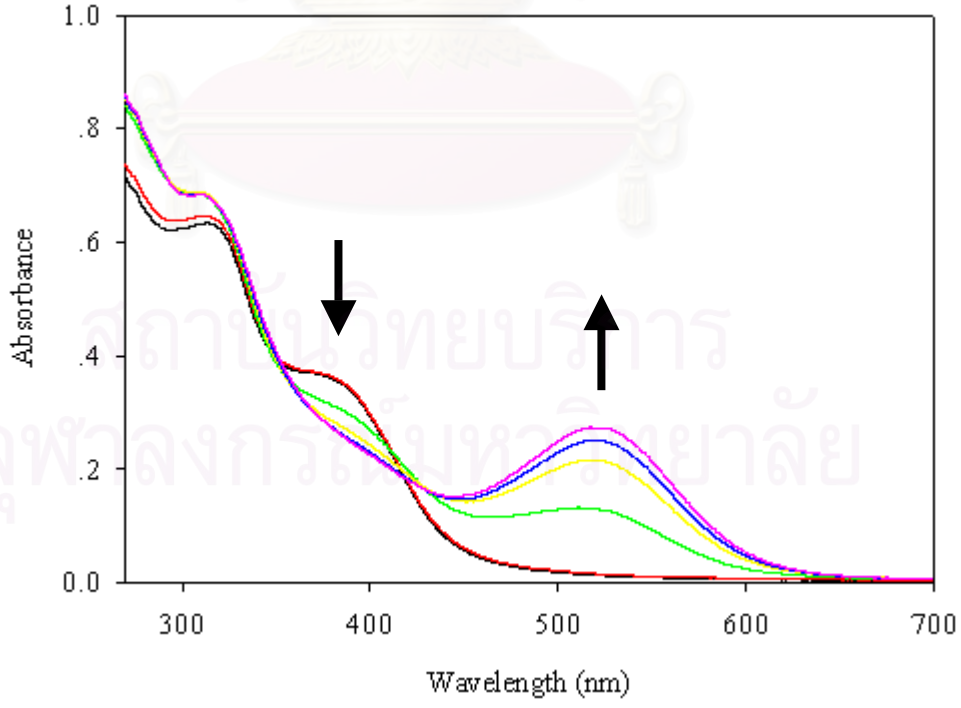



**Figure C.24** UV-vis titration spectra of **2d** (after irradiation) with azelate in DMSO ([**2d**] = 3.0 x $10^{-5}$ M, [azelate] = 0-25 equiv.).

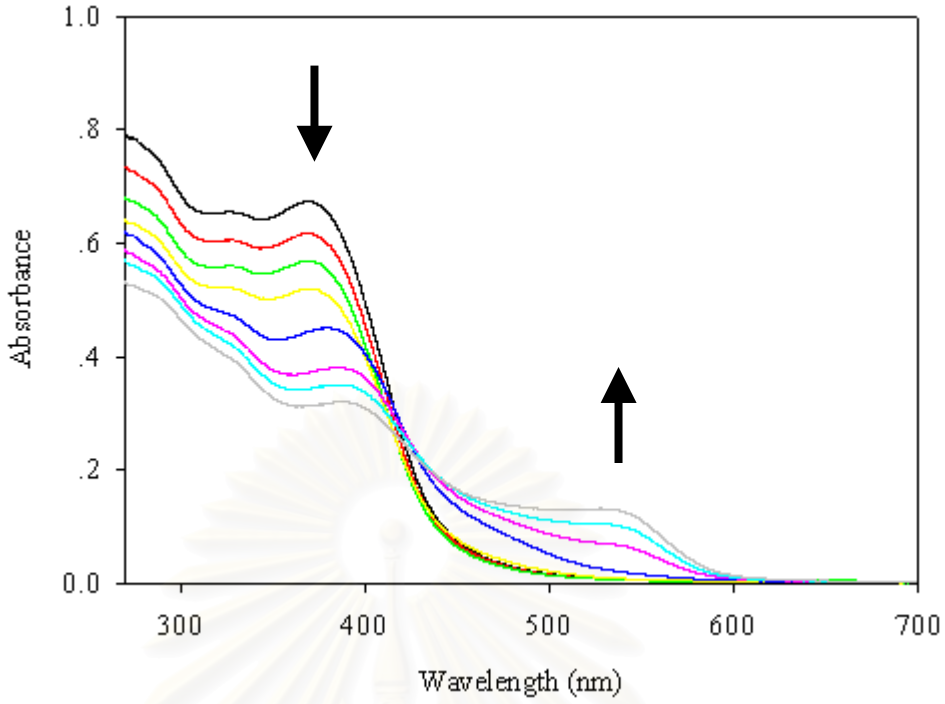



**Figure C.25** UV-vis titration spectra of **5d** (after irradiation) with acetate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [acetate] = 0-40 equiv.).

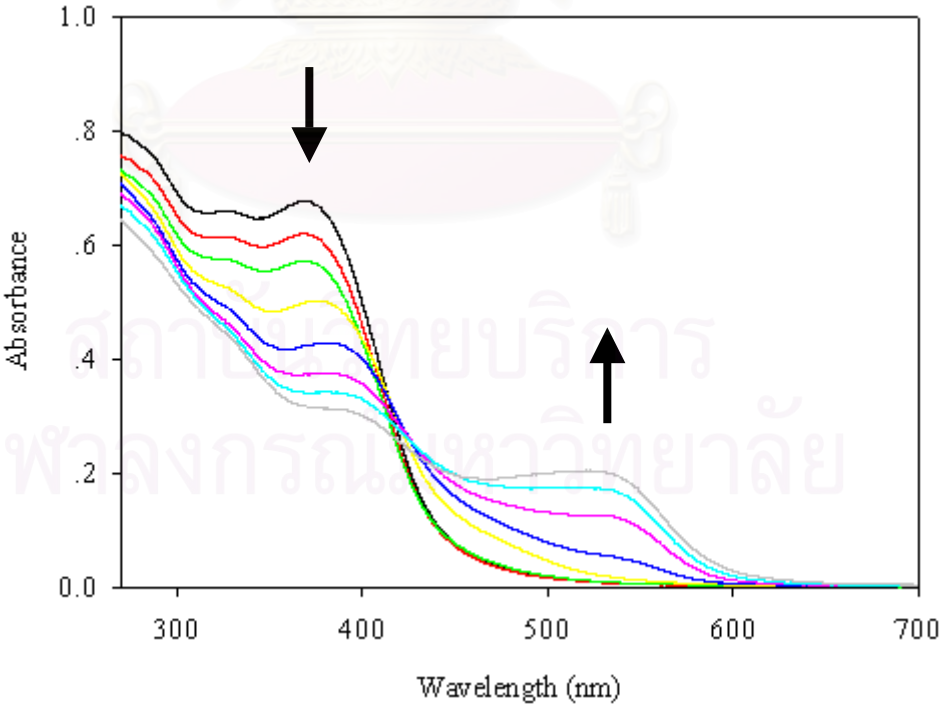



**Figure C.26** UV-vis titration spectra of **5d** (after irradiation) with oxalate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [oxalate] = 0-35 equiv.).

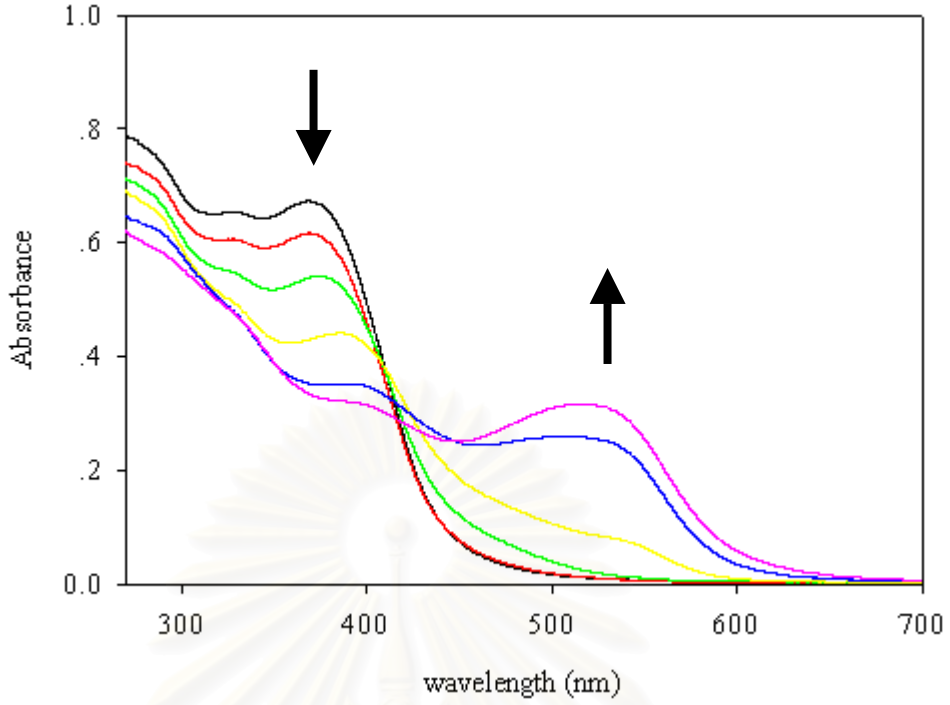



**Figure C.27** UV-vis titration spectra of **5d** (after irradiation) with malonate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [malonate] = 0-25 equiv.).

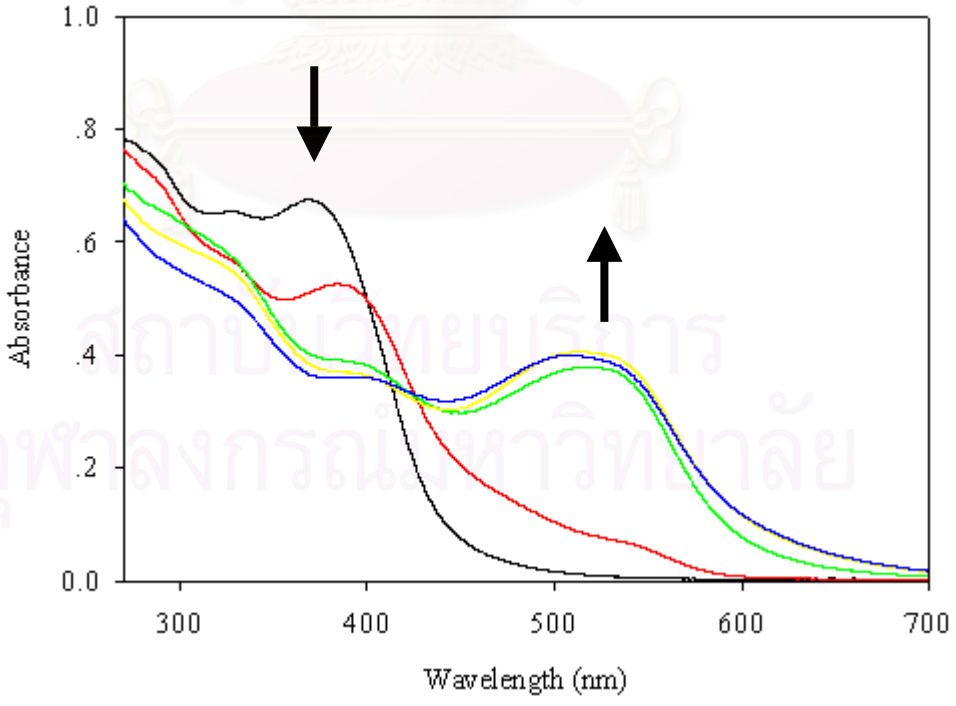



**Figure C.28** UV-vis titration spectra of **5d** (after irradiation) with succinate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [succinate] = 0-20 equiv.).

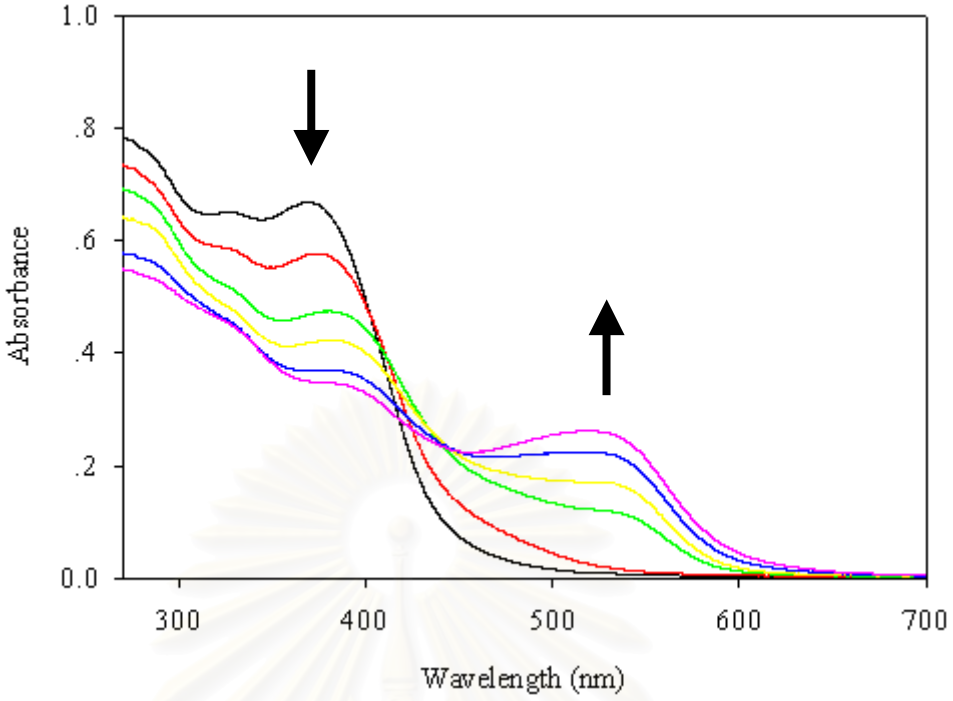



**Figure C.29** UV-vis titration spectra of **5d** (after irradiation) with glutarate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [glutarate] = 0-30 equiv.).

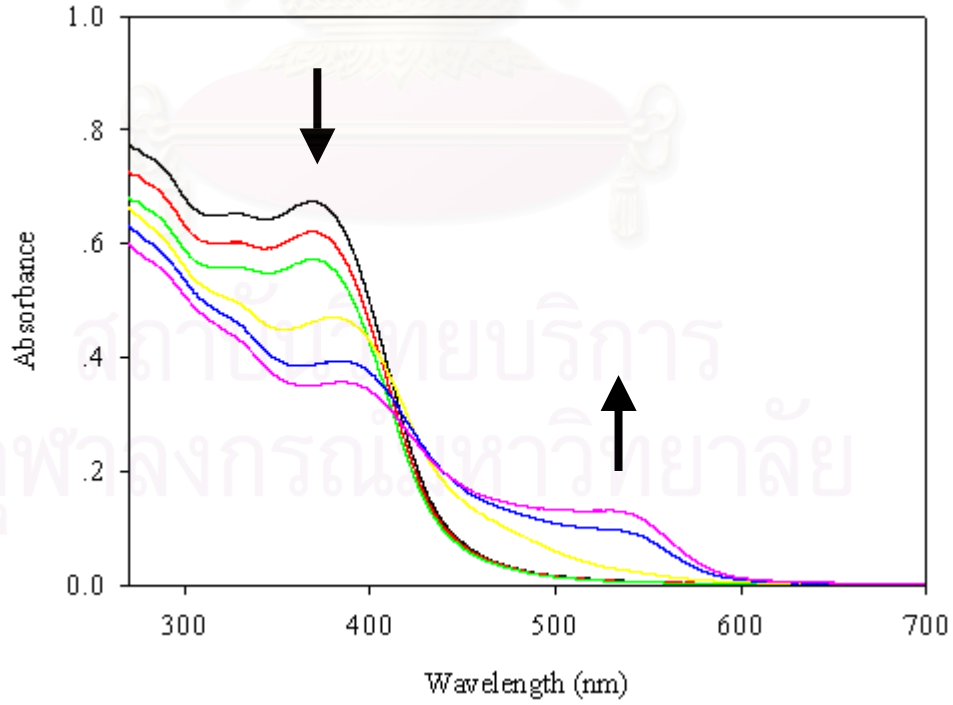



**Figure C.30** UV-vis titration spectra of **5d** (after irradiation) with adipate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [adipate] = 0-35 equiv.).

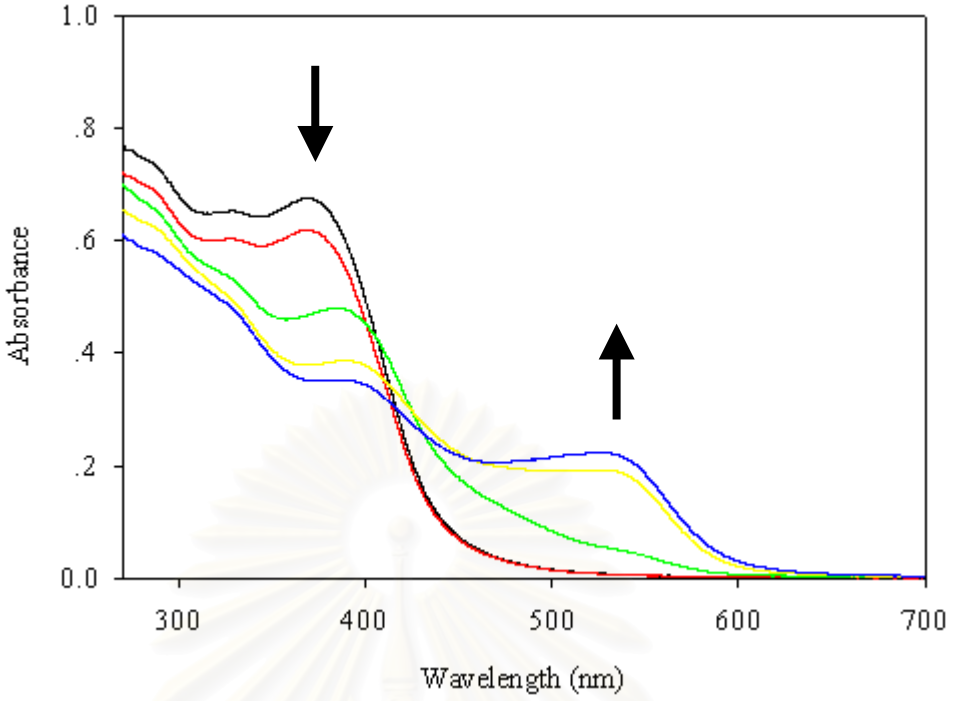



**Figure C.31** UV-vis titration spectra of **5d** (after irradiation) with pimelate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [pimelate] = 0-20 equiv.).

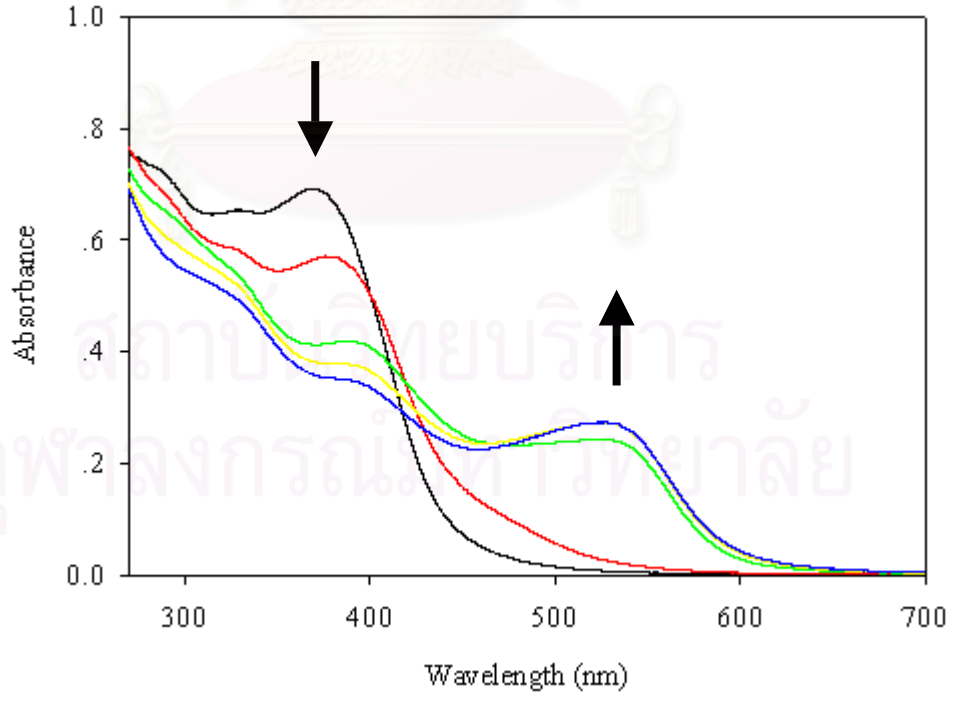



**Figure C.32** UV-vis titration spectra of **5d** (after irradiation) with azelate in DMSO ([**5d**] = 3.0 x $10^{-5}$ M, [azelate] = 0-20 equiv.).

# VITA

Miss Wanwisa Janrungroatsakul was born on May 13, 1976 in Sukhothai, Thailand. She graduated with a high school diploma from Dara Academy, Chiangmai in 1994. She received her Bachelor's degree of Science in Chemistry from Naresuan University in 1998. Since 2000, she has been a graduate student at the Department of Chemistry, Chulalongkorn University and become a member of the Supramolecular Chemistry Research Unit under supervision of Assistant Professor Dr. Thawatchai Tuntilani. She finished her Master's degree of Science in the academic year 2003.