

**LIQUID PHASE ^{13}C DYNAMIC NUCLEAR POLARIZATION
STUDY OF MONOSUBSTITUTED AROMATIC COMPOUNDS**

by

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(ABSTRACT)

In this work, liquid phase ^{13}C DNP experimental data were collected in a flow transfer system for different mono-substituted aromatic compounds, such as, anisole, nitrobenzene and halobenzenes. These substitute groups covered a wide range of electronic effects from strong electron donating groups to strong electron withdrawing groups.

Hammett linear free energy relationship was used to quantitatively study the electronic effect of substituent on the ^{13}C DNP enhancement. It was found that the ^{13}C DNP enhancements at meta and para positions exhibits a reasonable correlation. A better correlation of ^{13}C DNP enhancements with the Hammett inductive factor was observed.

A large scalar dominated enhancement at ipso (C-1) position was observed for iodobenzene. This suggests that facile transfer of spin polarization to the C-1 carbon via the highly polarizable iodine atom is possible and the dominate electron transfer mechanism for this system.

A model of polarization transfer via spin diffusion of abundant ^1H spins was examined. The results indicate that it is not important.

This thesis is dedicated to my parents and my wife.

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CHAPTER 1. INTRODUCTION

1.1 General Background

Purcell and Bloch and their co-workers first discovered the nuclear resonance effect in 1945[1,2]. Since then, this physics experiment has shown great interest for chemists, for this made it possible to use the technique of NMR as a spectroscopic method for studying chemical compounds.

However, NMR has always suffered from the low sensitivity due to the extremely small energy differences involved in nuclear spin transitions. For example, the population rate between higher and lower energy levels at room temperature for ^{13}C nuclei in a field of 4.7 T, which corresponds to a resonance frequency of 50.2 MHz, is 1.000008. The population difference is thus very small, even for the most sensitive nucleus ^1H . The detection limits are in the range of $10^{-3} \sim 10^{-6}\text{g}$, which is two to three orders less sensitive in magnitude than other spectroscopic methods such as mass spectroscopy, fluorescence spectroscopy[9]. In the past 50 years, a lot of techniques have been developed to improve the sensitivity of NMR[3,4]. Generally, there are three ways that can be used to increase the sensitivity. The first one is to increase the magnetic field. The second one is to lower the sample temperature. These two methods can only improve the signal-to-noise ratio by one order in magnitude. The third one is to use the double magnetic resonance technique in which the polarization transfer process is involved. Generally speaking, for any polarization transfer technique, the theoretical signal enhancement is proportional to γ_s/γ_I . γ_s is the magnetogyric ratio of some sensitive nuclear spin usually ^1H or electron spin. γ_I is the magnetogyric ratio of insensitive nuclei such as ^{13}C and ^{15}N . Nuclear-nuclear polarization

transfer techniques such as INEPT (insensitive nuclei enhanced by polarization transfer)[57,58,59] and DEPT (distortionless enhancement by polarization transfer)[60,61] can only increase the signal-to-noise by one order or less. This is mainly because the difference of gyromagnetic ratio (γ) between sensitive nucleus and insensitive nucleus is so small. Comparing to the γ of nuclear spin, the γ of electron spin is much larger which is two to three orders larger in magnitude than the nuclear spin. Electron-nuclear double resonance technique, which is also called dynamic nuclear polarization (DNP), provides a very powerful and cheap approach to increase the sensitivity of the observed NMR signals. For example, an enhanced factor of 660 and 2640 for ^1H and ^{13}C nuclei, respectively, can be predicted.

As mentioned above DNP is an electron-nuclear double resonance technique, the system subjected to DNP study usually contains of two non-identical spins: a nuclear spin system which comes from solution and an unpaired electron spin system which comes from the free radical. In solution, due to random molecular motion, the unpaired electron spins interact with the nuclear spins. Because this kind of intermolecular interaction is spatial and time dependent, the DNP technique not only can be used to dramatically improve the sensitivity of the NMR signal but also can be used to study weak intermolecular interactions, such as the molecular motion, mean distances for species in solutions, and weak radical/solvent complex formation[5,6,7,8].

1.2 Goal of Present Research

Carbon-thirteen NMR has played a very important role in organic compounds structure elucidation in liquids. However, due to very low natural abundance of ^{13}C and low gyromagnetic ratio, ^{13}C NMR has always suffered the great disadvantage of very low sensitivity. The DNP technique is a potential valuable tool in enhancing these weak NMR signals. Great efforts have been made to study ^{13}C DNP. According to previous ^{13}C DNP studies of monosubstituted aromatic compounds[9,10], it is hard to understand if there is any relationship between ^{13}C DNP enhancements of ring carbon and different substituted groups. Thus the major objectives of this research work are: 1) to further reveal the

association between the different substituted groups with the ^{13}C DNP enhancements of ring carbon, 2) to study the mechanism of electron spin density transfer between TEMPO and the carbon nuclei, and 3) to study the possibility of the intramolecular spin density transfer within the benzene ring.

CHAPTER 2. BASIC THEORY OF DNP IN LIQUIDS

2.1 General Explanation

Dynamic nuclear polarization (DNP) is a double resonance technique. In a normal DNP experiment, a stable free radical is added into the sample solution usually at a concentration of $0.001 \sim 0.1\text{M}$. When a nucleus with spin quantum number $I=1/2$ is placed in a static magnetic field, the Zeeman effect will cause the spin energy level of the nuclear spin split into two, $+1/2$ and $-1/2$. The relative population difference of the nuclear spins is called polarization. At equilibrium conditions, the spin populations in the higher and lower spins energy level follow the Boltzmann distribution. If free radical is added into this solution, due to the random molecular motion, the unpaired electron spins, which comes from the free radical, will interact with the nuclear spins. This interaction is called nuclear-electron coupling. This kind of nuclear-electron coupled system is subject to DNP study. Experimentally, the nuclear resonance is observed at the same times or right after the irradiation of an electron resonance in the same sample.

For an electron and nuclear coupled system with spin quantum number S_z , $I_z=\pm 1/2$, the energy level diagram is shown in Figure 2.1.

The possible states are denoted by $+-$, $++$, $--$ and $-+$. The plus or minus sign by convention represents the spins aligning with or against the magnetic field while the first sign refers to the electron spin S and the second sign to the nuclear spin I .

From the viewpoint of energy level, the lowest nuclear magnetic energy level is labeled

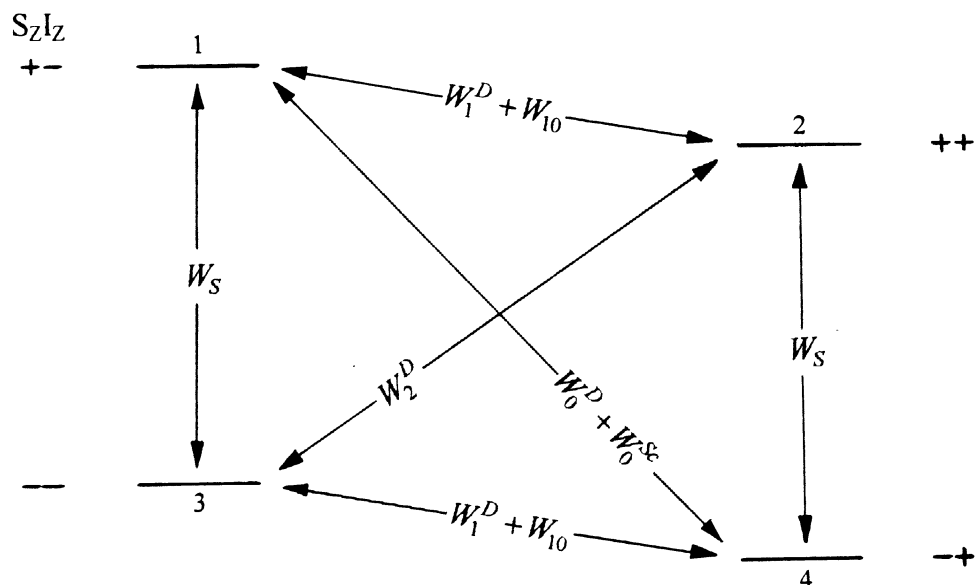


Figure 2.1. Energy Level Diagram of the Nucleus-Electron Spin Coupled System with $I=1/2$ and $S=1/2$ (Cited from Ref. 9).

plus, and because the magnetic moment of the electron has the opposite sign to that of the nuclear, the lower electron magnetic level is labeled minus.

In this diagram, W_i represents the nuclear relaxation transition probability. The transitions between the energy levels 1-2, 3-4, 1-3 and 2-4 are single quantum transitions that are theoretically allowed. Specifically, the transitions 1-2 and 3-4 are the nuclear transitions which involves changes in the I_z spin quantum number of $-1/2$ to $+1/2$ and of $+1/2$ to $-1/2$. These transitions can be observed in the NMR spectrum. The transitions 1-3 and 2-4 are the electron transitions which involve changes in the S_z spin quantum number of $+1/2$ to $-1/2$ and of $-1/2$ to $+1/2$. These transitions can be saturated by the microwave radiation. For the electron-nuclear coupled system, the rapid random diffusion of the molecule ensures that the solute molecules are near a free radical many times during the nuclear relaxation time. This strong pairwise interaction between the electron and nuclear

magnetic dipoles can induce two spin transitions coupled together in which the electron and nucleus make simultaneous flips.

Based on the type of interaction between electron and nucleus, there are four important coupled forms. The S.I. and S.I₊ transitions represent the dipolar coupling, the S.I₊ and S.I. represent scalar coupling.

For an electron-nuclear coupled system, at thermal equilibrium, there is more electron spin in the lower energy level than in the higher level. In the double resonance experiment, first the electron transition W_s of the free radical is strongly saturated. This will make the populations of the electron at low and high energy levels tend to be equal. This means that some of the population is transferred from low energy levels **1** and **3** to high energy levels **2** and **4**. After the saturation of the electron spin transition, a relaxation process will restore the population at each different energy level back to the equilibrium condition. For electron nuclear scalar coupling, the dominant W_0^{Sc} relaxation will cause the nucleus to perform an I. to I₊ transition simultaneously and the result is that nuclei originally in the high nuclear energy level are transferred to lower energy level. Thus the population of lower nuclear level becomes greatly increased. This causes an increase in the nuclear population differences between I. and I₊ spin levels and therefore the NMR signal intensity is increased. Specifically, the nuclear population at lower energy level N₊ is much larger than the population at higher energy level N. and an enhanced positive NMR absorption signal will be observed. On the other hand, if the dipolar transition is the dominant relaxation process, the W_{2D} relaxation will cause an I₊ to I. nuclear spin transition resulting in the nuclear population of N. to be larger than N₊. An enhanced negative emission NMR signal will be observed.

2.2 Basic Equations for Liquid DNP

A quantity used to measure the nuclear population difference between higher and lower level spins is termed polarization. For a nucleus with spin quantum number I, the nuclear polarization is generally expressed as[11]

$$P_I = \frac{1}{I} \frac{\sum_m m N_m}{\sum_m N_m} = \frac{1}{I} \langle I_z \rangle \quad (2.1)$$

where m is the magnetic quantum number corresponding to a distribution energy level in the magnetic field. The number of nuclear spins corresponding to the energy level m is N_m and the experimentally observable value of the nuclear spin operator I_z is $\langle I_z \rangle$.

The larger the nuclear polarization, the stronger the NMR signal. Thus, a quantitative understanding for the enhancement factor of DNP can begin by considering the rate of the population change for the individual energy states. At thermal equilibrium, the ratio of the population at the higher spin state N_- to the lower spin state N_+ is governed by a Boltzmann distribution, according to the following equation:

$$\frac{N_-}{N_+} = \exp\left(-\frac{h\nu}{KT}\right) \quad (2.2)$$

where T is the absolute temperature and K is Boltzmann constant.

For the ^{13}C nucleus in the magnetic field of 4.7 Tesla and at 293 K, the value for N_-/N_+ is approximately 1.000008. This value indicates a very small polarization. For an electron–nuclear coupled two spin system, the changing rate of the population N_{++} at $|++\rangle$ state can be expressed as[12]

$$\frac{dN_{++}}{dT} = -(W_1^D + W_{10} + W_2^D + W_s)(N_{++} - N_{++}^0) + W_2^D(N_{--} - N_{--}^0) + W_s(N_{-+} - N_{-+}^0) + (W_{10} + W_1^D)(N_{+-} - N_{+-}^0) \quad (2.3)$$

In this formula, the superscript zero represents the population of the Boltzmann equilibrium in the absence of a magnetic field. There are some similar equations for the other states. The relationship between the expectation value of nuclear spin $\langle I_z \rangle$ and electron spin $\langle S_z \rangle$ to the appropriate population difference are given as:

$$\langle I_z \rangle = k[(N_{++}-N_{+-})-(N_{-+}-N_{--})] \quad 2.4$$

$$\langle S_z \rangle = k[(N_{-+}-N_{++})-(N_{--}-N_{+-})] \quad 2.5$$

by combining equation 2.2 with 2.3 and 2.4, the changing rate of the observed NMR signal is given by:

$$\frac{d\langle I_z \rangle}{dt} = -(W_0^D + W_0^{Sc} + 2W_1^D + W_2^D + 2W_{10}^D)(\langle I_z \rangle - I_0) - (W_2^D - W_0^D - W_0^{Sc})(\langle S_z \rangle - S_0) \quad (2.6)$$

where I_0 and S_0 are the values of $\langle I_z \rangle$ and $\langle S_z \rangle$, respectively. At the steady state condition $d\langle I_z \rangle/dt = 0$, then equation 2.6 is reduced to

$$\langle I_z \rangle = I_0 + \left[\frac{W_2^D - W_0^D - W_0^{Sc}}{W_0^D + W_0^{Sc} + 2W_1^D + W_2^D + W_{10}^D} \right] (\langle S_z \rangle - S_0) \quad (2.7)$$

Finally, the detailed derivation of $\langle I_z \rangle$ in the form of nuclear transition probabilities has been performed by Solomon[13], and is expressed as

$$\langle I_z \rangle = I_0 \left\{ 1 + \frac{W_2^D - W_0^D - W_0^{Sc}}{W_0^D + W_0^{Sc} + 2W_1^D + W_2^D} \times \frac{W_0^D + W_0^{Sc} + 2W_1^D + W_2^D}{(W_0^D + W_0^{Sc} + 2W_1^D + W_2^D) + 2W_{10}^D} \times \frac{S_0 - \langle S_z \rangle}{S_0} \times \frac{S_0}{I_0} \right\} \quad (2.8)$$

In this formula, the three terms in the bracket have some physical meaning, and will be defined as follows:

Nuclear-electron coupling factor

$$r = \frac{W_2^D - W_0^D - W_0^{Sc}}{W_0^D + W_0^{Sc} + 2W_1^D + W_2^D} \quad (2.9)$$

Leakage factor

$$f = \frac{W_0^D + W_0^{Sc} + 2W_1^D + W_2^D}{(W_0^D + W_0^{Sc} + 2W_1^D + W_2^D) + 2W_{10}} \quad (2.10)$$

Saturation factor

$$S = \frac{S_0 - \langle S_z \rangle}{S_0} \quad (2.11)$$

substituting these factors in eq. 2.8 and using the relation $S_0/I_0 = \gamma_s/\gamma_I$, we will have:

$$\langle I_z \rangle = I_0(1 + \rho f s \gamma_s / \gamma_I) \quad 2.12$$

by rewriting equation 2.12 and defining the observed DNP enhancement as

$A_{obs} = (\langle I_z \rangle - I_0)/I_0$, the DNP enhancement A can be expressed as

$$A_{obs} = r f s \frac{g_s}{g_I} \quad (2.13)$$

The observed DNP enhancement A_{obs} can be determined experimentally and is dependent on experimental conditions. Its value can not be used to evaluate the experimental results. It needs to be converted to the ultimate enhancement A_{∞} . Under the condition of complete saturation ($s=1$) and total relaxation via electron-nuclear coupling ($f=1$), the ultimate DNP enhancement A_{∞} is defined as:

$$A_{\infty} = r \frac{g_s}{g_I} \quad (2.14)$$

In comparing equation 2.14 with equation 2.13, the ultimate DNP enhancement can be obtained easily via dividing the observed DNP enhancement by the f factor and s factor.

Among the three factors in the equation 2.13 the most important one is the coupling factor ρ . Also in Eq. 2.14, it can be seen that γ_s and γ_I are constant for certain nuclei. The ultimate DNP enhancement is only dependent on the coupling factor ρ and the intermolecular interaction. Therefore the coupling intensity and the coupling mechanism is solely contained in this factor. The coupling factor ρ can range from -1 for a pure scalar electron-nuclear interaction ($W_0^D = W_1^D = W_2^D = 0$) to +0.5 in the case of pure dipolar interaction ($W_0^{Sc} = 0$). In practice, both scalar and dipolar interactions can be present. According to equation 2.14, the ultimate DNP enhancement will range between $1/2(\gamma_s/\gamma_I)$ to $-\gamma_s/\gamma_I$. Specifically, if scalar relaxation is the dominant relaxation process ($W_0^{Sc} \gg W_2^D, W_0^D$), a positive scalar dominated enhancement will be observed. On the other hand, if dipolar relaxation dominates ($W_2^D, W_0^D \gg W_0^{Sc}$), a positive dipolar dominated enhancement will be observed.

The leakage factor f measures the nuclear relaxation time percentage which comes from the free radical among the total nuclear relaxation time. It determines the efficiency that the nuclear spin is relaxed by the electron spin. Experimentally, we can determine the f factor by the following equation:

$$f = 1 - \frac{T_0}{T_{10}} \quad (2.15)$$

where T_1 and T_{10} are the relaxation times of the sample in the presence and absence of free radical, respectively. The value of the f factor can range from 0 for no relaxation via electron-nuclear coupling to 1 for total relaxation via electron-nuclear coupling, depending on the concentration of free radical in the sample solution. The DNP enhancement can only be observed when the value of the f factor is larger than 0.8.

The third factor in equation 2.13 is the saturation factor S. This value is a measure of the efficiency of the saturation of the electron spin transition by the microwave power. The relationship between the expectation value of the electron spin moment $\langle S_z \rangle$ and the applied electromagnetic field strength B_{1s} is given by:

$$\langle S_z \rangle = \frac{S_0}{1 + g_s^2 B_{1s}^2 T_{1s} T_{2s}} \quad (2.16)$$

where T_{1s} and T_{2s} are the electron spin-lattice and spin-spin relaxation times. Substituting equation 2.16 into equation 2.11, we get:

$$S = \frac{g_s^2 B_{1s}^2 T_{1s} T_{2s}}{1 + g_s^2 B_{1s}^2 T_{1s} T_{2s}} \quad (2.17)$$

Now equation 2.13 can be rewritten as:

$$f = 1 - \frac{T_0}{T_{10}} \quad (2.18)$$

Experimentally, we can obtain the s factor easily by an extrapolation method[14]. Since $(B_{1s})^2$ is proportional to the microwave power P, equation 2.18 can be changed to the form:

$$\frac{1}{A} = \left(f r \frac{g_s}{g_I} \right)^{-1} \left(1 + \frac{1}{a P T_{1s} T_{2s}} \right) \quad (2.19)$$

where α is a constant. According to equation 2.19, a plot A^{-1} versus P^{-1} will give a straight line with intercept $(\rho f \gamma_S / \gamma_I)^{-1}$. The reciprocal of this intercept is the enhancement at $S = 1$. Therefore the S factor under certain microwave power can be extrapolated by making a ratio of the observed enhancement at that microwave power P to the enhancement at complete saturation condition $S = 1$.

$$(W_0^D = W_1^D = W_2^D = 0)$$

The reciprocal of the intercept gives the enhancement with the correction of saturation factor. The slope of the plot tells of the efficiency of the microwave power.

2.3 The Interaction for a Nuclear-Electron Coupled Two Spin System

2.3.1 The Hamiltonian of the Nuclear-Electron Interaction

For a nuclear-electron coupled system, the spin Hamiltonian of magnetic interaction is expressed as:[15]

$$\hat{H} = -g_S \hbar B_0 \hat{S}_z - g_I \hbar B_0 \hat{I}_z + \hat{H}_{IS}(t) + \hat{H}_{II}(t) + \hat{H}_{SS}(t) \quad (2.21)$$

where γ_S and γ_I are the electron and nuclear spin gyromagnetic ratios, respectively. $\hat{S}_z$ and $\hat{I}_z$ are the electron and nuclear spin operators. In this formula, the first two terms are electron and nuclear Zeeman terms, respectively. These describe the interaction of electron and nuclear spin with the external steady magnetic field B_0 . The last three terms are the respective time-dependent nuclear-electron, nuclear-nuclear, and electron-electron interaction terms. Among these three coupling terms, $\hat{H}_{IS}(t)$ is the most important one for the DNP experiment. This time-dependent electron-nuclear interaction solely gives rise to the electron spin induced relaxation and the DNP enhancement. According to the mechanism of nuclear-electron interaction, the $\hat{H}_{SI}(t)$ can be further reduced into two

terms. One is called the dipolar interaction term $\hat{H}_{SI}^D(t)$. The other term is called the scalar interaction term, $\hat{H}_{SI}^{Sc}(t)$.

$$\hat{H}_{SI} = \hat{H}_{SI}^D + \hat{H}_{SI}^{Sc} \quad (2.22)$$

2.3.2 The Dipolar Interaction

Dipolar interaction is analogous to classic dipolar coupling between two bar magnets. The dipolar interaction Hamiltonian is expressed as

$$\hat{H}_{SI}^D = \mathbf{g}_I \mathbf{g}_S \hbar^2 \left[\frac{3(\vec{r} \cdot \hat{S})(\vec{r} \cdot \hat{I})}{r^5} - \frac{\hat{S} \cdot \vec{r}}{r^3} \right] \quad (2.23)$$

Since the dipolar coupling arises from the interaction of the nuclear and electron magnetic dipoles, this interaction takes place whenever an unpaired electron and a magnetic nucleus are present in the same solution. In low viscosity liquids, due to the random molecular motion, the dipolar part of the interaction is averaged to zero and does not contribute to the time-independent interactions. But it does provide a time-dependent interaction (relaxation and DNP). Three types of modulation models have been proposed. Each of which is characterized by corresponding spectral density functions $J_i(\omega)$ and the molecular correlation time τ_i .

1). Relative transnational diffusion model[16]

In this model, the electron and nuclear spins are in the center of the different molecules and no complexation of free radical and sample molecule forms. The time-dependent interaction arises from fluctuation in the interspin distance. The spectral density function is expressed as[17-19]

$$J_i(\omega) \cong [1 + 0.9(\omega\tau_i)^{1/2} + 1.5(\omega\tau_i)^{3/2}]^{-1} \quad (2.24)$$

In this formula, ω_l is the Larmor frequency of the coupled nuclear-electron pair, and takes the values of ω_l , $\omega_l + \omega_s$, $\omega_s - \omega_l$ for the transition probability of single, double and zero quantum, respectively. The transnational correlation time τ_t is characterized by the following equation,[20]

$$\tau_t = \frac{12\eta}{5k} \frac{d_t^2}{\left(\frac{r_l r_s}{r_l + r_s} \right) T} \quad (2.25)$$

where d_t is the closest distance between the free radical and the receptor molecule. The symbols r_l and r_s are the radii of the sample molecule and the free radical molecule, and η is the viscosity of the solution. The radical induced dipolar transition probability is given by

$$2W_1^D = 3W_0^D = W_{\frac{2}{2}}^D = \frac{2\eta}{5} g_s^2 g_l^2 \hbar^2 \tau_t N_e d_t^{-3} J_t(\omega_l) \quad (2.26)$$

where N_e is the concentration of the unpaired electron.

2). Rotational diffusion model[21]

This model is effective for the situation that S and I spins are in the same molecule such as nuclear and free radical spins are in the same molecule or free radical and sample molecule form a tight bond complex. The transition probability is given by

$$2W_1^D = 3W_0^D = W_{\frac{2}{2}}^D = \frac{3}{10} g_s^2 g_l^2 \hbar^2 \tau_t \left(\frac{n_p N_e}{N_p} \right) d_r^{-6} J_r(\omega_l) \quad (2.27)$$

where n_p is the number of the receptor nuclei bound near each electron, N_p is the concentration of total nuclei, d_r is the average pair radius of the rotating adduct. The spectral density function $J_r(\omega_l)$ is given by

$$J(\omega_i) = \frac{1}{1 + \omega_i^2 \tau_r^2} \quad (2.28)$$

where τ_r , the rotational correlation time is expressed as:

$$\tau_r = \frac{4\pi b^3 \hbar}{3kT} \quad (2.29)$$

where b is the effective tumbling radius of the molecular complex.

3). Mixed transnational and rotational diffusion[22]

This model is helpful in explaining the situation that the sample molecule and the free radical form a weak complex, such as hydrogen bonding. The spectral density function for this model is given by [22]

$$J_D(\omega_i) = \frac{2 n_e \tau_t}{3 d^3} \left[f_t(\omega_i \tau_t) + R \frac{\tau_r}{\tau_t} f_r(\omega_i \tau_r) \right], \quad (2.30)$$

In this formula, n_e is the number of the unpaired electrons in the unit volume. R is a measure of the relative influence of the rotational diffusion to the mixed modulation of the dipolar coupling. It is given by

$$R = \frac{3m d_t^3}{4\pi b^6 n_l} \quad (2.31)$$

where m is the average number of nuclei associated with a radical molecule. The reduced spectral density function $f_t(\omega \tau_t)$ and $f_r(\omega \tau_r)$ are defined as

$$f_t(\omega \tau_t) = \frac{J_D^t(\omega_i)}{J_D^t(0)} \quad \text{and} \quad f_r(\omega \tau_r) = \frac{J_D^r(\omega_i)}{J_D^r(0)} \quad (2.32)$$

Overall, the dipolar interaction is always present in the solution and is distance dependent. It can provide some information about the distance involving molecular collisions.

2.3.3 The Scalar Interaction

The time-dependent Hamiltonian for the scalar interaction between the nuclear spin and the unpaired electron spin is given by

$$\hat{H}_{SI}^{Sc}(t) = A_{SI} \hat{I} \cdot \hat{S} \quad (2.33)$$

Where A_{SI} is the hyperfine coupling constant. It can be expressed as

$$A_{SI} = -\gamma_S \gamma_I \hbar |\psi(0)|^2 \quad (2.34)$$

$\psi(0)$ represents the wave function of the unpaired electron at the nucleus. Scalar coupling involves the electron spin density transfer from the unpaired electron to the S orbital of the nucleus. There are two possible mechanisms which can be used to describe this interaction, a diffusion model or a sticking model.

1) The Sticking Model[13,23,24]

In this model, there is a finite scalar interaction only during the time when the electron spin and the nuclear spin are “stuck” together, such as in the case of forming a weak complex between the free radical and the sample molecule. When these two spins are stuck together, the scalar interaction is characterized by the coupling constant A . When the complex falls apart, the coupling constant becomes zero and there will be no scalar interaction. The scalar transition probability and the spectral density function for this model can be expressed as

$$W_D^{Sc} = \frac{1}{2} \left(\frac{A}{\hbar} \right)^2 \left(\frac{t_{Sc}}{1 + (W_S + W_I)^2 t_{Sc}^2} \right) \quad (2.35)$$

$$J_{A_{SI}}(\omega_S) = \frac{m A_{SI}^2}{n_I \hbar^2} \frac{\tau_{Sc}}{1 + \omega_S^2 \tau_{Sc}^2} \quad (2.36)$$

where τ_{Sc} is the scalar correlation time. The coupling constant per unit frequency time 2π , $A_{Sc}/\hbar$, is a measure of the induced electron spin density.

2). The diffusion model[16]

In the diffusion model, the scalar interaction is assumed to be a function of the distance between the I and S spins. As in the dipolar case, the variation of distance r with time is responsible for the time dependence of interaction. Thus, unlike the sticking model, the unpaired electron density produced at the nuclei is not at one instant finite and then zero. It reaches its maximum value as the radical and sample molecule collide and then decays to zero again as the molecules recoil from each other. Since the scalar interaction could involve the electron-orbital overlap with the nucleus, the interspin distance can be very short, and thus a steep function of the internuclear distance. The hyperfine coupling constant is assumed to have the form

$$A_{IS} = \frac{A d}{r_{IS}} \exp[-\lambda (r_{IS} - d)] \quad (2.37)$$

where r_{IS} is the distance between I and S spins, d is the distance of closest approach between I and S. A and λ is a constant. The scalar transition probability for the diffusion model is expressed as

$$W_0^{Sc} = \frac{N_e p A^2 d^3}{2 I D (\omega_S \tau_{Sc})^{1/2}} \left\{ 1 + \exp(\omega_S \tau_{Sc})^{1/2} \left[\sin(\omega_S \tau_{Sc})^{1/2} - \cos(\omega_S \tau_{Sc})^{1/2} \right] \right\} \quad (2.38)$$

where $\omega = \omega_S + \omega_I$, N_e is the number of spins, τ_s is the scalar correlation time and D is the average diffusion constant of the radical and receptor nuclei.

2.3.4 Mixed Scalar and Dipolar Interactions

As mentioned before, the dipolar interactions are always present between the electron and nuclei. For some nuclei, such as ^{13}C , the scalar interaction may also be present in the system. When both interactions are present, it is necessary to combine one of the dipolar interaction models with one of the model for the scalar interaction. Thus, there may be many combinations. It is dependent on the particular system.

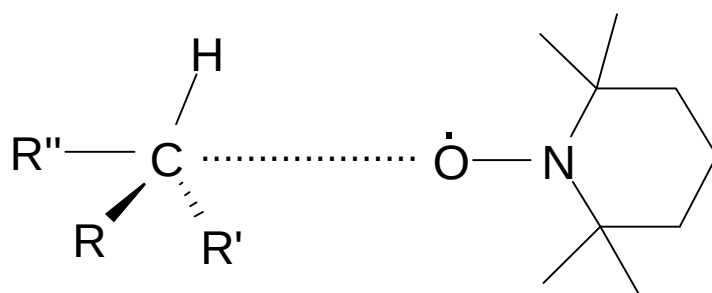
2.4 The Three Spin Effect

All the basic DNP equations discussed above are based on the assumption that the polarization of the nuclear spins is exclusively determined by the interaction with the electron spins and no interaction with other nuclear spin. We have considered only the direct electron-nuclear two spins coupled interactions. However, in some case, the monitored nucleus can interact indirectly with the electron spin via the third spin. For example, the ^{13}C polarization is determined not only by the presence of the unpaired electron, but also by the presence of the protons. Fig.2.2 illustrates the direct and indirect electron- ^{13}C interaction. Fig. 2.2 (a) is the usual direct transfer of magnetization from the unpaired electron to the carbon atom, (b) shows the indirect three spin transfer of the magnetization from the electron spin first to the proton then via the polarized proton spin to the carbon. The ^{13}C three spin enhancement ($A_{3\text{-spin}}$) is expressed by [25] :

$$A_{3\text{-spin}} = -\mathbf{r}_C^H \mathbf{f}_C^H \mathbf{r}_H \mathbf{f}_C^H \frac{g_S}{g_C} \quad (2.39)$$

where $\mathbf{r}_C^H$ is the proton-carbon coupling factor and $\mathbf{f}_C^H$ is the fraction of total ^{13}C nuclear relaxation rate due to proton-carbon dipolar coupling. Thus, in the case of the three-spin effect, the enhancement is corrected as:

(a)



(b)

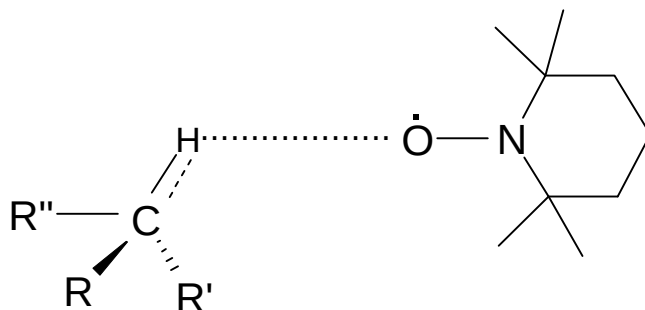


Figure 2.2 Nucleus-Electron Coupling Systems: (a) Two Spin Coupling System; (b) Three Spin Coupling System

$$A = \left(\mathbf{r}_C^S f_C^S - \mathbf{r}_C^H f_C^H \mathbf{r}_H^S f_H^S \right) s \frac{g_s}{g_C} \quad (2.40)$$

From Eq. 2.38, it can be found the indirect three spin transfer of the magnetization will result in positive ^{13}C DNP enhancement. Therefore, the three spin effect will decrease the

dipolar dominated ^{13}C DNP enhancements and increase the scalar dominated ^{13}C DNP enhancements in the solution. For a particular system, the significance of the three spin effect depends on the effectiveness of the carbon-proton interaction.

Generally, the three spin effect can be eliminated by two ways. the first is by using triple irradiation experiment. Under the triple irradiation condition, the ^{13}C enhancement is given by [26] :

$$A = r_c^S f_c^S S \frac{g_S}{g_C} + r_c^H f_c^H S^H \frac{g_H}{g_C} \quad (2.41)$$

In the equation 2.41, the first term is identical to the enhancement for the two spin system. Because of $\gamma_S \gg \gamma_H$, so the second term can be neglected. The second method that can be used to avoid three spin effect is by using high radical concentration. Under this condition, the relaxation of carbon via proton is suppressed, $f_c^H \cong 0$. Therefore, the second term in the Eq. 2.40 can be eliminated. In this work, this method was used.

CHAPTER 3. INSTRUMENTATION AND EXPERIMENTAL SECTION

3.1 Introduction

3.1.1 General Description

In our laboratory, a liquid-liquid intermolecular transfer (LLIT) DNP experiment has been developed [27-31], in which a free radical (in this work, TEMPO, 2,2,6,6-tetramethylpiperidine 1-oxyl,) is dissolved in the solution containing sample molecules. During the experiment, the nitrogen degassed sample, conducted by the PEEK tubing, is pumped through the low and high magnetic field and then back to the sample reservoir. A HPLC pump with flow rates of 2~8 mL/min is used to make the sample solution recycle. The electron transition was saturated by the microwave power in the low magnetic field and then the enhanced DNP signal was detected in the high magnetic field. All of the experiment was performed at room temperature and under non-spinning and non-locking conditions. For the ^{13}C DNP experiment, the ^1H broad band decoupling technique is used.

3.1.2 Build-up Loss and Transfer Loss[9]

In order to make the electron transition completely saturated. A sufficient residence time ($3\sim 5 T_1$) of the sample in the low magnetic field is necessary. A reduction in signal intensity will occur for a given nuclei if the flow rate is too rapid to ensure complete build-up of the polarization. On the other side, after the establishment of the fully polarization, the enhanced DNP signal must be detected before the nucleus relaxes to equilibrium. This requires the amount of time spent in the transfer from low to high field should be short relative to nuclear-electron relaxation time. Transfer losses will result in a reduction of the

DNP enhancement. Overall, the improper choice of the flow rate can have a detrimental effect on the magnitude of the subsequent DNP enhancement.

3.1.3 Sample Degas

Oxygen is a paramagnetic molecule which has two unpaired electrons. In sample solution, the dissolved oxygen will compete with TEMPO radicals for the interaction with the monitored nuclei[32] and result in decreasing the DNP enhancement. So, in all experiments, the liquids were degassed by bubbling dry nitrogen through the solution prior to and during the experiment.

3.2 The Flow Transfer DNP Instrument

3.2.1 Magnetic Field

A diagram of the instrumental apparatus used in this work is shown in Fig 3.1. There are two magnetic fields. A low variable electromagnet field with a range of 0 to 0.6 T, which is used to saturate electron transition, is placed directly under a 4.7 T superconducting magnet. In order to minimize the influence of the electromagnet on the homogeneity of superconducting magnet, these two magnets are arranged at 1.2m apart. In this work, the strength of low magnet was controlled at 0.33T. In the high field, the NMR detecting probe is a homemade Helmholtz coil probe with two channels. One is the proton channel with the resonance frequency of 199.5 MHz. The other one is ^{13}C channel with the resonance frequency of 50.2 MHz. Four standard capacitors were used for tuning and matching.

3.2.2. Sample Cells for the NMR Probe and EPR Cavity

The flow cell used in NMR probe is a self-made glass cell. The size of this cell is about 2.5 cm long with a volume of 100 μl . A ceramic tube, which can stand the high pressure arising from the high flow rates, bought from Omega Engineering, Inc. is chosen to serve as the cell in the low field. The structure and the dimensions of the cells are shown in Figure 3.2. These two sample cells in the low and high magnetic field were connected by Polyetheretherkenton(PEEK) tubing with 0.007" O.D..

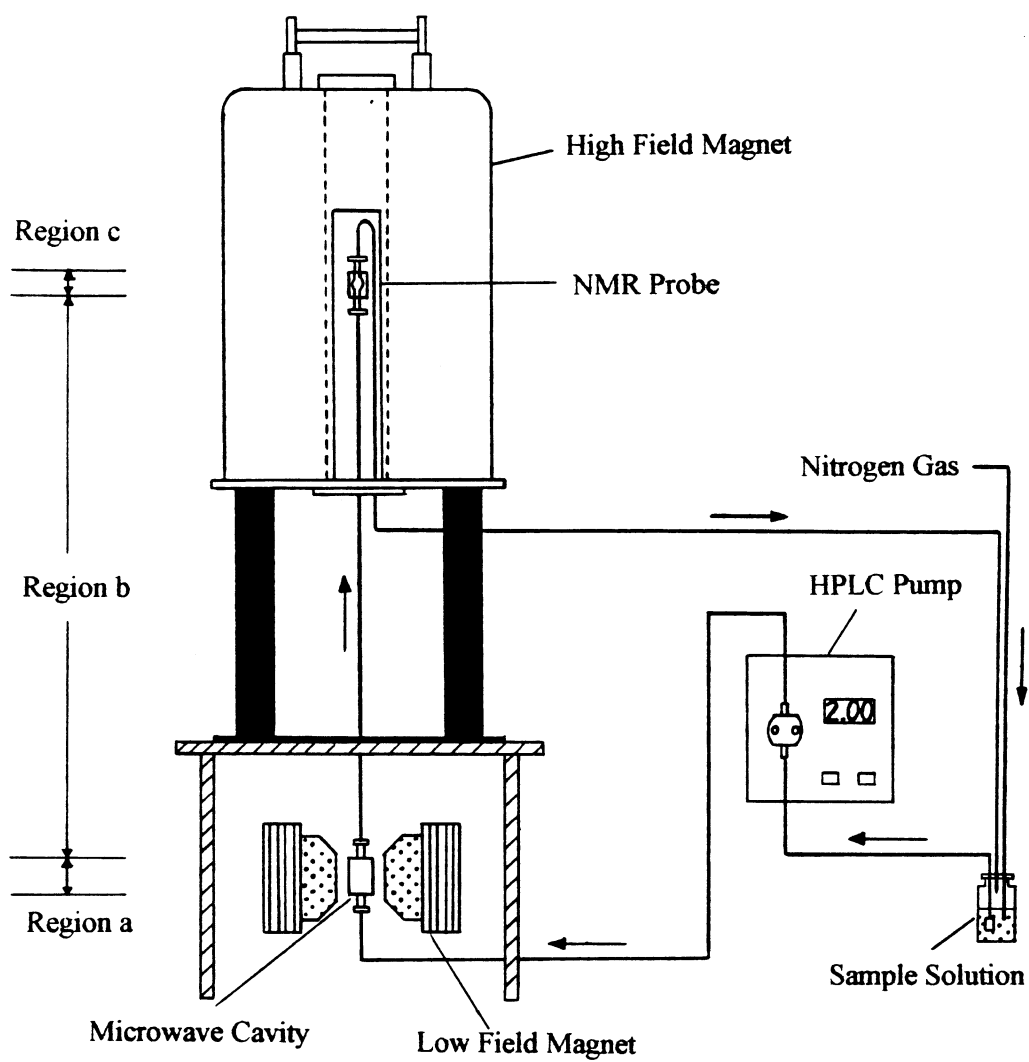


Figure 3.1 Low to High Magnetic Field Transfer DNP Experimental Apparatus (Cited From Ref. 10)

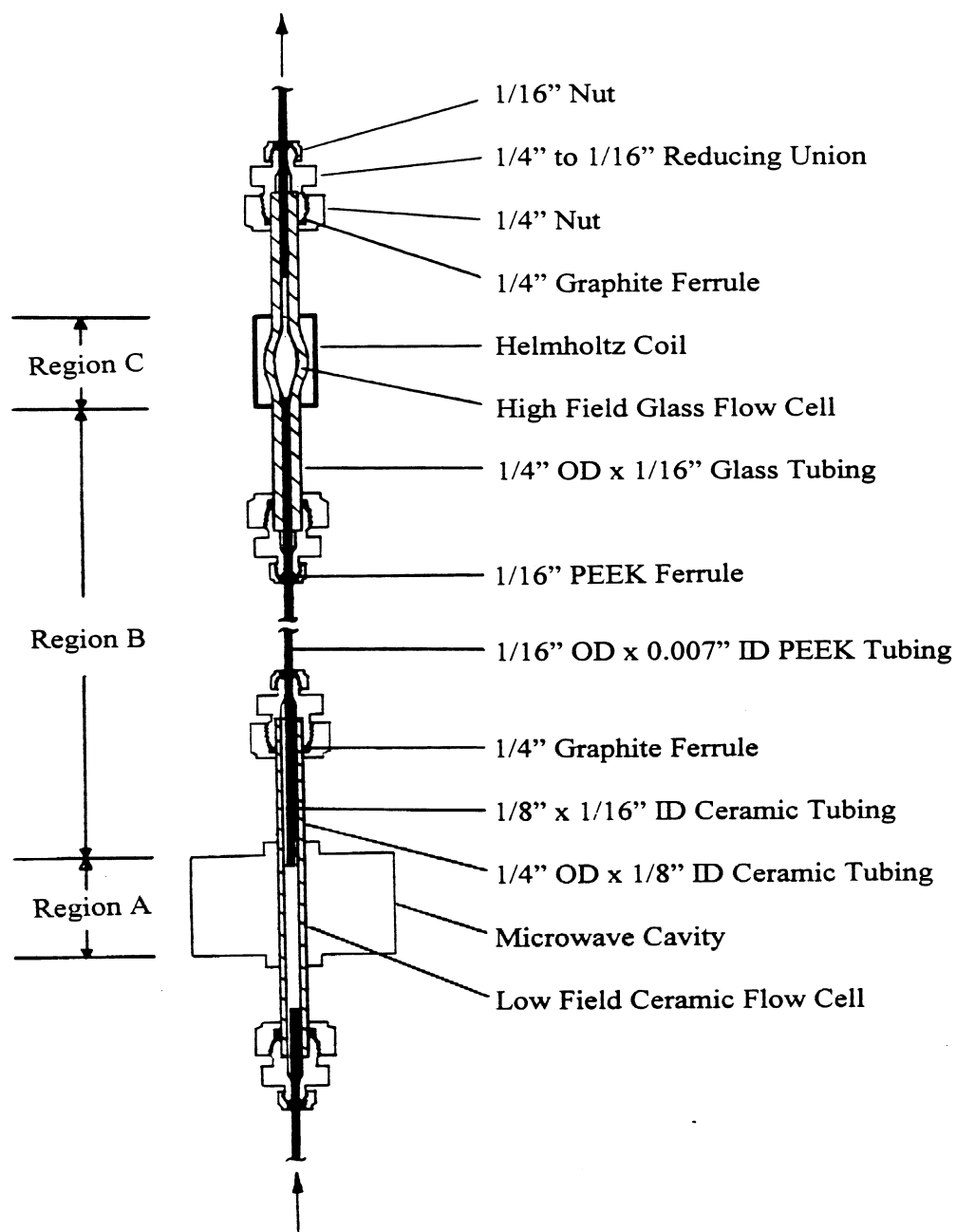


Figure 3.2. Low to High Field Flow Cells (Cited From Ref. 10)

3.2.3. Others

In the low fields, the sample in a ceramic cell is placed in a microwave TE₁₀₂ cavity . The microwave frequency around 9.3 GHz was used to saturate the unpaired electron transition of free radical is provided by the Klystron source of an EPR spectrometer. The microwave power is amplified by a Varian K series TWT amplifier which is adjustable by an attenuator in the range of 2 ~ 20 Watts. A HPLC pump with a flow range of 1 ~ 9 ml/min was used to recycle the liquid sample.

3.3 Chemicals

All of the reagents and solvents were obtained commercially. The Benzene-d₆ is purchased from the Isotec Inc.. All other chemicals were purchased from Aldrich Chemical Co. and used directly without further purification. TEMPO (2,2,6,6-tetramethyl-1-piperidinyloxy) was used as free radical. This is mainly because that: 1) it is chemically inert and very stable, 2) it is a relatively small molecule and the unpaired electron is highly localized on the n-o group, (3) it is commercially available.

3.4 Determination of Ultimate Enhancement (A_{∞})

3.4.1 Determination of the Leakage Factor f

According to equation 2.10, the leakage factor can be obtained by measuring the spin lattice relaxation rates of the sample solution in the presence and the absence of the free radical at the low magnetic field where DNP is developed. Because of the sensitivity and the spectral resolution limitations in the low field, in this work, the relaxation times measured in high magnetic field were used to approximate those measured in low field. The high field spin-lattice relaxation times were measured at 4.7 T magnetic field using a standard inverse recovery sequence (180° - τ - 90° -T)[35]. The sample was sufficiently deoxygenated before the T_1 measurement. The leakage factor f was then calculated based on the high field NMR data. The relative standard deviation for T_1 measurements was between 2~7%. A sample curve of the T_1 measurement is illustrated in Figure 3.3.

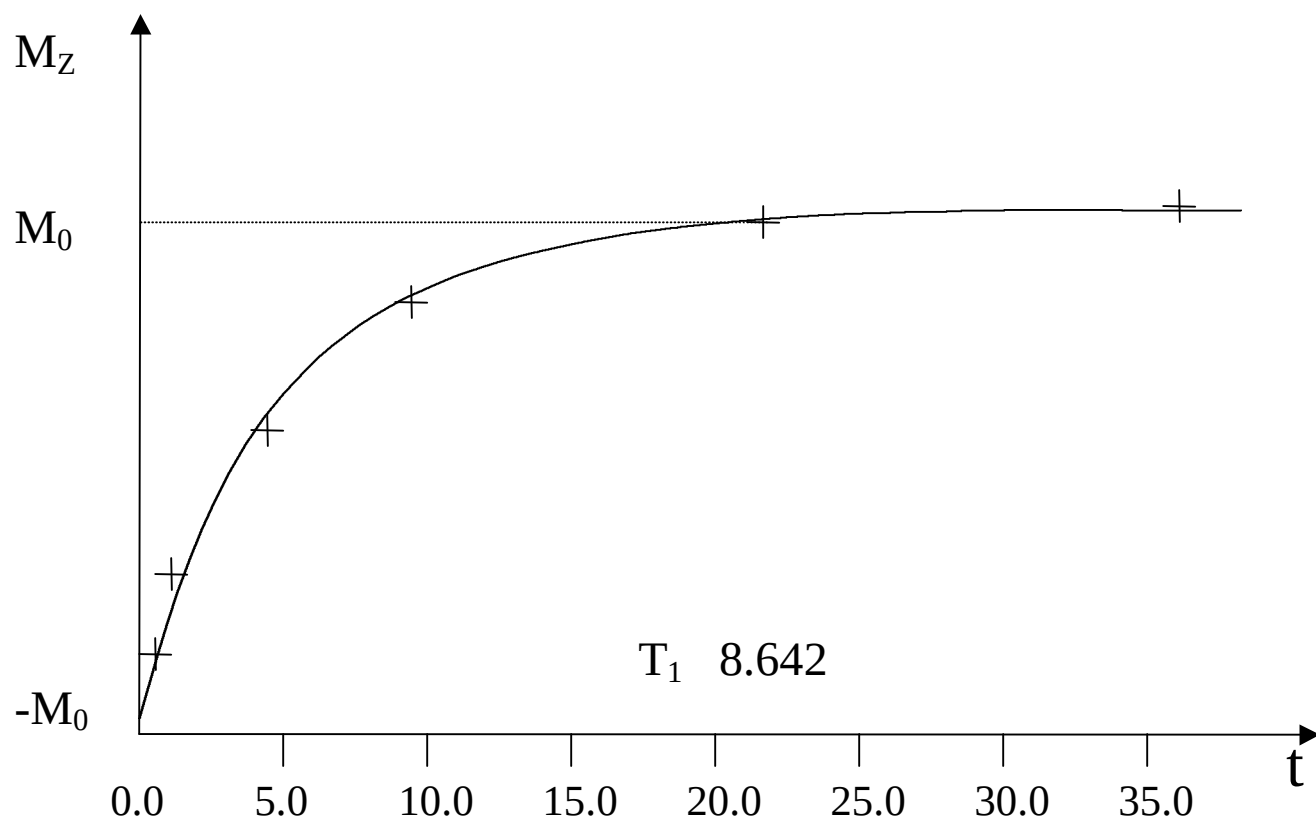


Figure 3.3 ^{13}C 200 MHz Spin-Lattice Relaxation Time Plot for 0.5M Anisole/0.1M TEMPO in Cyclohexane

3.4.2 Determination of Saturation Factor (s)

First, ^{13}C LLIT DNP enhancement $A_{\text{obs}}(P)$ was measured by using different microwave power. Experimentally, equation 3.1 can be used to calculate the enhancement at different power $A_{\text{obs}}(P)$

$$A_{\text{obs}}(P) = \frac{M_z^* - M_z^{\text{HL}}}{M_0^{\text{H}}} \quad (3.1)$$

where M_z^* is the peak height of the enhanced NMR signal at certain microwave power P . M_z^{HL} is the peak height of the flow NMR signal in the absence of the microwave power. M_0^H is the peak height of the static NMR signal. Then the extrapolated DNP enhancement $A_{obs}^{s=1}(P \rightarrow \infty)$ can be obtained from the intercept of the plot of $[A_{obs}(P)]^{-1}$ versus P^{-1} at optimized flow rate. Finally, the s factor at a particular microwave power can be easily calculated by eq. 2.19. A sample DNP power plot is shown in Figure 3.4.

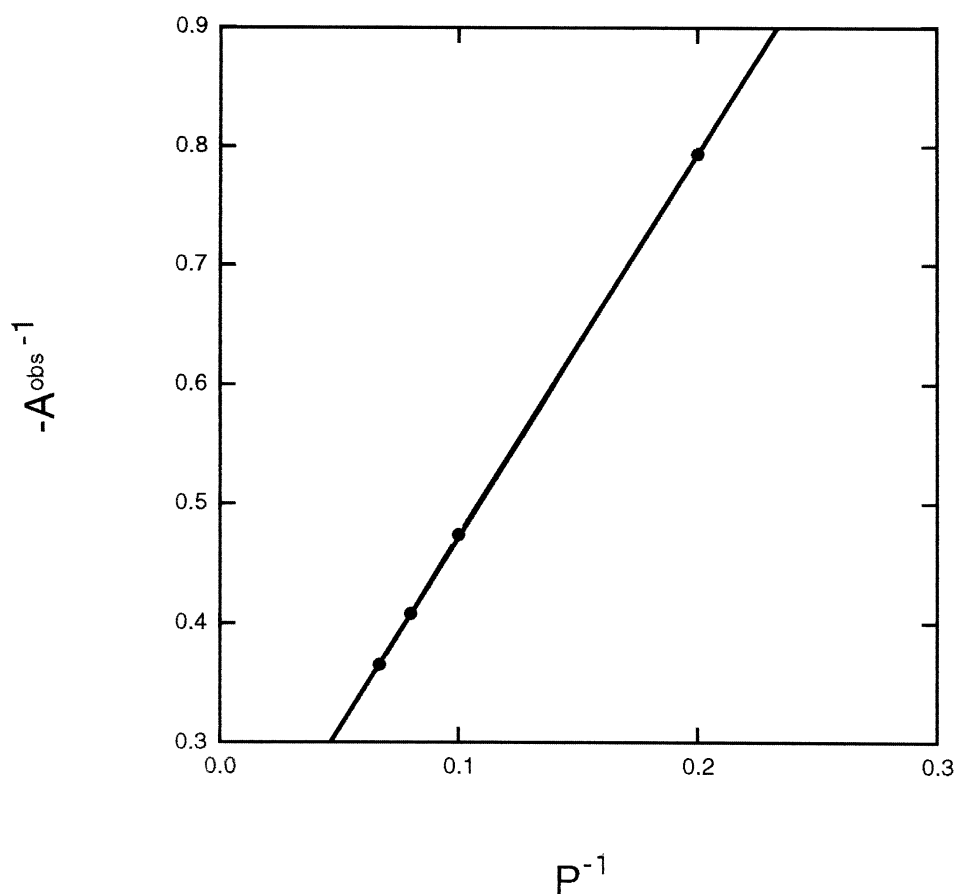


Figure 3.4 ^{13}C Power Plot of Cyclohexane

3.4.3 Experiment Determination of the Ultimate DNP Enhancement A_{∞}

There are two ways that can be used to calculate the ultimate DNP enhancement. One is called the exhaustive method[27,28,33,34]. This method takes into account as many variable factors that may cause an error to the final result as possible, such as the low to high magnetic field strength change, f and s factors. It is closely correlated to the flow transfer DNP system, so that the calculated result better matched the true value. The disadvantage of this method is that it requires the instrument to be stable and it is very time consuming, since the data have to be obtained for a whole range of flow rates. Another way to determine the ultimate DNP enhancement is called ratio method[10,36]. In this work, most of the DNP data were collected and processed by the ratio method. This is mainly because some of the sample solutions cannot be readily studied by the exhaustive method which is more demanding either on the sensitivity and stability of the instrument or the experimental time. The procedure of the ratio method is much simple. The s factor is assumed to be same for all the nuclei in a given experiment. No flow plot or power plot has to be made in the ratio method. The experiment and calculation for the ultimate DNP enhancement A_{∞} by using ratio method includes several steps. In detail:

1. to get the peak height of the ^{13}C static NMR, flow NMR and DNP spectra
2. to get the observed ^{13}C DNP enhancement A_{obs} for the flow transfer system by using equation 3.1
3. to convert the observed ^{13}C DNP enhancement A_{obs} obtained from the flow transfer system to the static DNP system A_s . A model for the calculation of the ultimate enhancement in the low to high magnetic field transfer DNP experiment has been established by K.H. Tsai and H.C. Dorn^{9,28}. The formula for the converting A_{obs} to A_s is given as

$$A_s(P) = \frac{K \cdot A_{\text{obs}}(P)}{\left[1 - e^{-\frac{V_a}{T_{1a} \cdot F}} \right] \cdot \left[e^{-\left(\frac{V_b}{T_{1b}} + \frac{V_c}{T_{1c}} \right) \frac{1}{F}} \right]} \quad (3.2)$$

where T_{1a} , T_{1b} and T_{1c} are the nuclear relaxation times in the regions a, b, and c, respectively; V_a , V_b and V_c are the sample solution volumes in the regions a, b, and c, respectively; F is the flow rate ($\mu\text{L}/\text{sec.}$) of the sample solution; K is the high to low magnetic field strength ratio which equals 14.2. By making some approximation:

$$\begin{aligned} T_{1a} &\cong T_{1b} \cong T_{1c}, \\ V_a &\cong 160\mu\text{L}, V_b+V_c \cong 120\mu\text{L}, \end{aligned}$$

The static DNP enhancement A_s can be expressed by the experimental measurable quantities in the following formula:

$$A_s(P) = \frac{K \cdot A_{obs}(P) \cdot e^{\frac{120}{T_{1c} \cdot F}}}{1 - e^{\frac{160}{T_{1c} \cdot F}}} \quad (3.3)$$

4. to get the ultimate DNP enhancement by the following equation:

$$A_{\infty} = A_{\infty}^{ref} \left[A_s(P) / A_{ref}(P) \right] \left[f_{ref} / f_s \right] \quad (3.4)$$

where A_{∞}^{ref} is the ultimate DNP enhancement of the reference nucleus (in this work ^{13}C in the cyclohexane is used as reference); $A_s(P)$ and $A_{ref}(P)$ are the observed DNP enhancements for the respective nucleus and the reference nucleus measured under microwave power P ; f_{ref} and f_s are the f factors of the reference nucleus and sample nucleus, respectively.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. ^{13}C Studies of the Substituent Effects on the Monosubstituted Aromatic Compounds

4.1.1 Introduction

Previous work has demonstrated that the DNP technique provides a potentially powerful tool for the investigation of the interaction between various molecules and free radicals. Several flow transfer ^{13}C DNP studies of substituted aromatic compounds have been previously reported, such as, chlorobenzene, 1,3,5-trichlorobenzene, 1,2-dichlorobenzene, nitrobenzene and toluene[9,10]. Table 4.1 gives the enhancement results for these studies. It can be seen that the carbon nucleus attached to the chlorine for chlorobenzene exhibited a large negative dipolar dominated enhancement, whereas the carbon adjacent to the C-1 showed a large scalar dominated enhancement (see Figure 1. for carbon assignments). Similar results were obtained for 1,3,5-trichlorobenzene. The large scalar enhancement at the carbon sites adjacent to the chlorinated carbon position was interpreted in terms of weak complexation of the TEMPO radical with the weakly acidic hydrogens attached to the carbons of interest in the aromatic moiety. The driving force for the hydrogen-TEMPO complexation was attributed to the presence of the electron attracting chlorine atom on adjacent carbon in the benzene ring. The ^{13}C DNP results of 1,2-dichlorobenzene exhibits a reasonable trend with the results of mono- and tri-chlorobenzene (see Table 4.1). For nitrobenzene, the carbon site attached to the nitro group shows a large dipolar dominated DNP enhancement; whereas, the carbon adjacent to it exhibits a large scalar dominated enhancement. In contrast to nitrobenzene, all the carbon sites of toluene show negative dipolar dominated enhancements. Especially the aromatic carbons at the ortho, para and meta position which exhibit strong dipolar enhancements in contrast to the results for nitrobenzene. A direct spin density delocalization model[10] was developed to explain the experimental results. Over all, from the view point of the substituent electronic effect,

the results in Table 4.1 show a trend of the electron attracting groups, such as chlorine or the nitro group, promoting scalar enhancement of all aromatic carbons (except for the carbon C-1 directly connected to the functional group). Whereas, the electron releasing methyl group yields dipolar enhancement.

Table 4.1 ^{13}C Ultimate DNP Enhancements of 1-chlorobenzene, 1,2-dichlorobenzene, 1,3,5-trichlorobenzene, Nitrobenzene and Toluene

Type	Compound	C-1	C-2	C-3	C-4	C-5	C-6
A	1-Chlorobenzene ^a	-100	140	-17	-23	-17	140
B	1,2-Dichlorobenzene ^a	-120	-120	178	70	70	178
C	1,3,5-Trichlorobenzene ^b	-330	290	-330	290	-330	290
A	Nitrobenzene ^b	-572	587	198	366	198	587
A	Toluene ^b	-423	-185	-196	-192	-196	-185

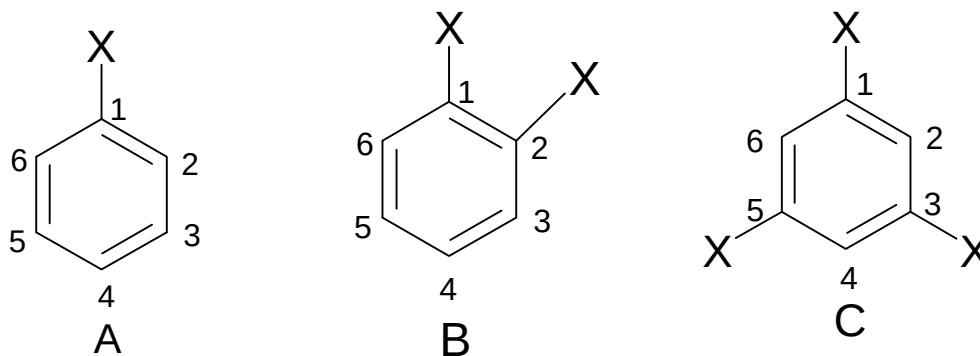


Figure 1. peak assignment

Note:

- Liquid phase ^{13}C DNP experiments were furnished by Dr. K. H. Tsai in 1990(Ref. 9).
- Liquid phase ^{13}C DNP experiments were furnished by Dr. Z. Sun in 1996(Ref. 10).

All prior mono-substituted benzene DNP studies focused on analyzing substituent effects of the same substituent on different positions in the same molecule. To date, there are no systematic studies of the influence of different substituent groups on the ^{13}C DNP enhancement of monosubstituted aromatics. Therefore, in the present research, a variety of aromatic compounds were studied in order to observe substituent electronic effects on ^{13}C DNP enhancements in monosubstituted aromatics. Since the ^{13}C DNP enhancement is dependent on electron donating or electron withdrawing properties of the substituent, the correlation study will provide a delicate probe of these weak intermolecular interaction effects between the free radical (TEMPO) and the aromatic system by the substituent. In the present work, eleven mono-substituted aromatic compounds were studied by the ^{13}C transfer DNP technique. These compounds were chosen on the basis of electronic effects of the substituents and range from strong electron donating groups to strong electron withdrawing groups.

4.1.2 Results and Discussion

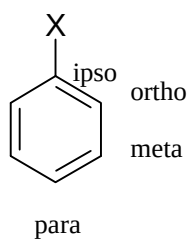
The ^{13}C DNP enhancement data is summarized in Table 4.2 . Three sample ^{13}C DNP results and spectra of benzonitrile, anisole and benzaldehyde are presented in Table 4.3-4.5 and illustrated in Figure 4.6-4.8. It can be seen (Table 4.2) that the carbon site attached to the substituted group exhibits a large dipolar dominated DNP enhancement, except for the case of iodobenzene. The much larger dipolar dominated enhancement is probably due to a smaller scalar contribution and lack of three-spin effect[9]. The large scalar dominated enhancement in iodobenzene may involve a special spin transfer mechanism which will be discussed in the next section.

The ^{13}C DNP enhancements results in Table 4.2 also show that ortho, meta and para position exhibit large scalar dominated enhancements for compounds with electron-withdrawing groups (F, Cl, Br, I, CN, CHO, NO_2). Whereas, the dipolar dominated enhancements are observed in compounds with electron donating substituted groups (OCH_3 , CH_3 , NH_2). The ^{13}C DNP results also show that larger magnitude scalar enhancements for most compound follow the order of ortho > meta > para. These results

indicate that the ^{13}C DNP enhancement have a definitive relationship with substituent electronic effects.

Table 4.2 ^{13}C Ultimate DNP Enhancements for the Mono-Substituted Benzene/ TEMPO System

X	Ipsso	Ortho	Meta	Para	Other
H	-199	-199	-199	-199	
F	-572	63	71	-51	
Cl	-478	95	11	-32	
Br	-170	147	50	-9	
I	478	111	39	15	
CN	-281	171	98	22	-204
CHO	-456	131	93	78	373
NO_2^*	-572	582	198	366	
OCH_3	-457	-42	-61	-64	266
CH_3	-562	-179	-153	-207	-187
NH_2^*	-318	-22	-131	-145	



Note:

* These two A_∞ values were determined by Z. Sun in a collaborative study.

These results can be interpreted based on the following effects:

1) the inductive effect acts via the σ -bond system and decrease rapidly with distance from the substituent, 2) the mesomeric effect produces, as a result of interaction through the π -electron system, an electron excess or deficit (depending on the nature of the substituent) at the ortho and para position and 3) the steric effect which is greatest at the C-1 (ipso) and C-2/6 (ortho) position.

Over the past fifty years, the Hammett equation has been widely used in the study of reactivity in substituted aromatic compounds. It also provides a quantitative way to analyze the electronic effect of substituents and the corresponding the ^{13}C DNP enhancement.

Hammett found for a large number of reactions of meta and para substituted benzene derivatives, a plot of the logarithm of the equilibrium (K) constants for one reaction (ionization of benzoic acids) vs $\log(K)$ for another reaction (ionization of phenylacetic acids) exhibited a linear relationship[51-53]. This type of relationship is called a linear free energy relationship. The equation of the line is[55]

$$\log\left(\frac{K}{K_0}\right) = \rho\sigma \quad (4.1)$$

where ρ is referred to as the reaction constant which is a measure of the sensitivity of the equilibrium constant to the changes in the σ value of the substituent. σ is referred to as the substituent constant. The sign and magnitude of σ for a substituent is a measure of the capacity of the electron-donating (-) or electron-withdrawing (+) ability of a given group. The σ constant is further expressed as σ_m and σ_p for meta and para positions, respectively^{51,53}.

Figure 4.1 shows a plot of meta ^{13}C DNP enhancements against σ_m . It can be seen that the points for the meta substituents form nearly a straight line with a correlation

coefficient of 0.9358. The plot of para ^{13}C DNP enhancements from Table 4.2 versus σ_p (in Figure 4.2) also exhibits a clear trend except for the deviation of three points corresponding to the substituents $-\text{OCH}_3$, $-\text{NO}_2$ and $-\text{NH}_2$. The large deviation for these three compounds may be due to the strong mesomeric effect of

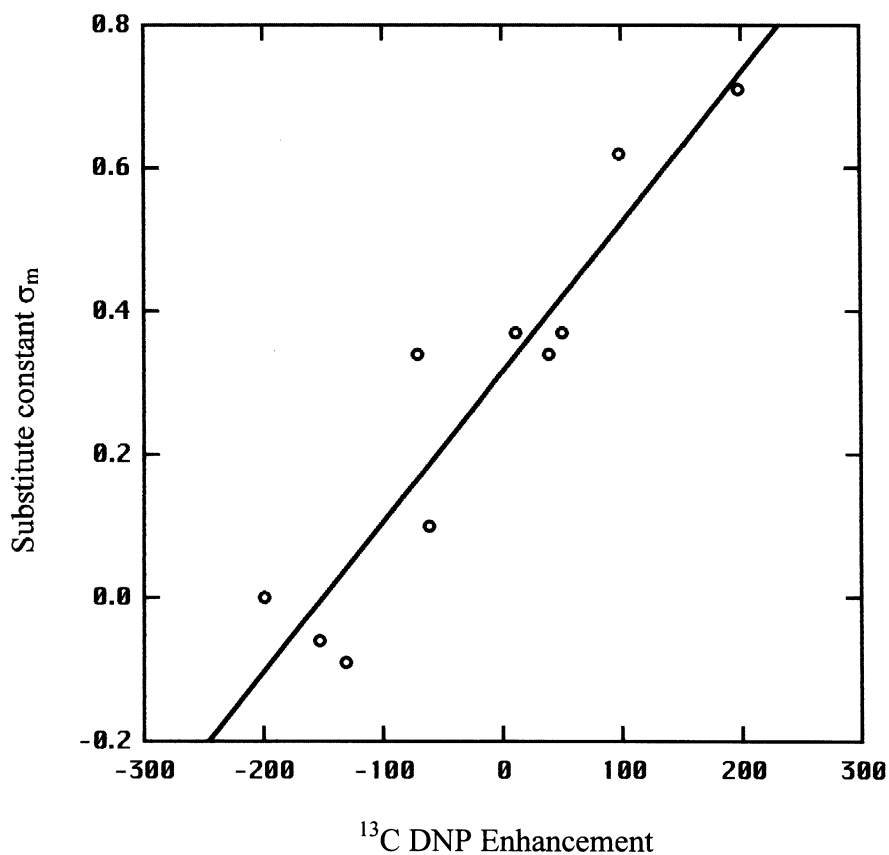


Figure 4.1. Meta ^{13}C DNP Enhancements as a Function of the Hammett σ_m Constant (from the comprehensive data given by Exner⁵⁴)

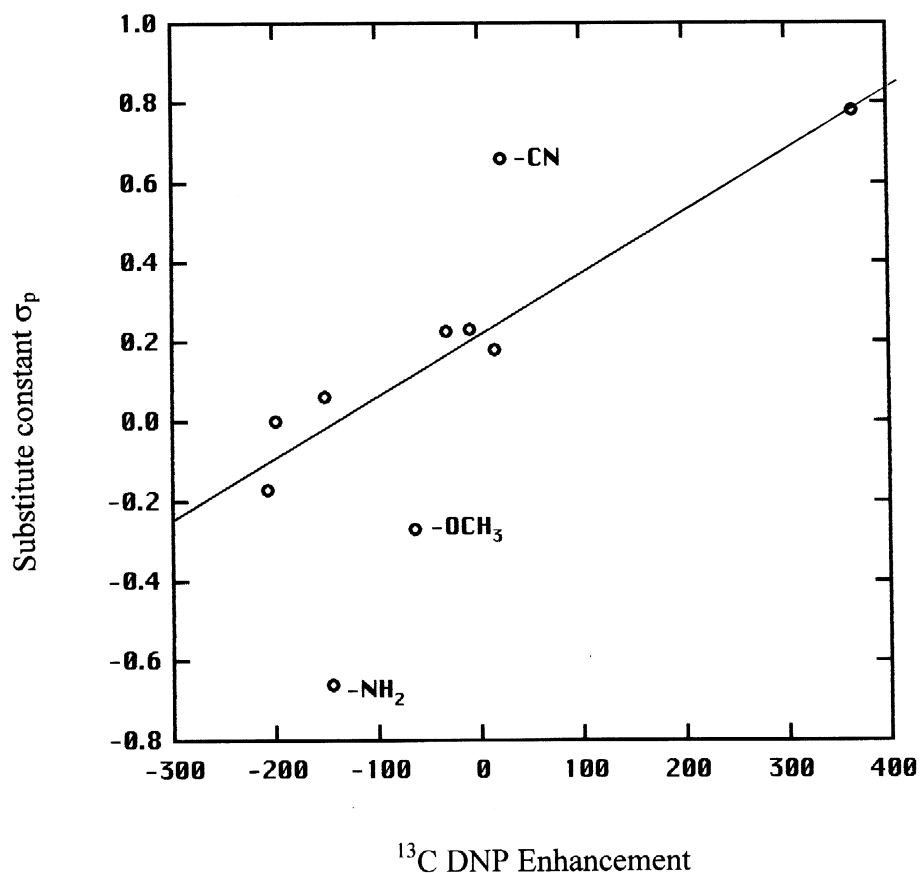


Figure 4.2. Para ^{13}C DNP Enhancements as a Function of the Hammett σ_p Constant (from the comprehensive data given by Exner[54])

these substituents. The better correlation of the data at the meta position is possibly due to the lower importance of mesomeric effects transmitted to the meta position in these compounds.

It is well recognized that a drawback of the normal Hammett constant σ is that it combines both inductive and mesomeric effects in one parameter, either σ_m or σ_p . The

modification of the normal Hammett constant by separating the parameters into their components representing σ_I and σ_R which are Hammett inductive and resonance constants, respectively. The correlation plot of meta and para ^{13}C DNP enhancements versus $\sigma_{R[54]}$ constant was attempted, and only a linear relationship was obtained with correlation coefficient 0.6575 and 0.7346. The plot of meta and para ^{13}C DNP enhancements versus σ_I are shown in Figure 4.3 and 4.4. Comparison of Figure 4.1 and 4.2 with Figure 4.3 and

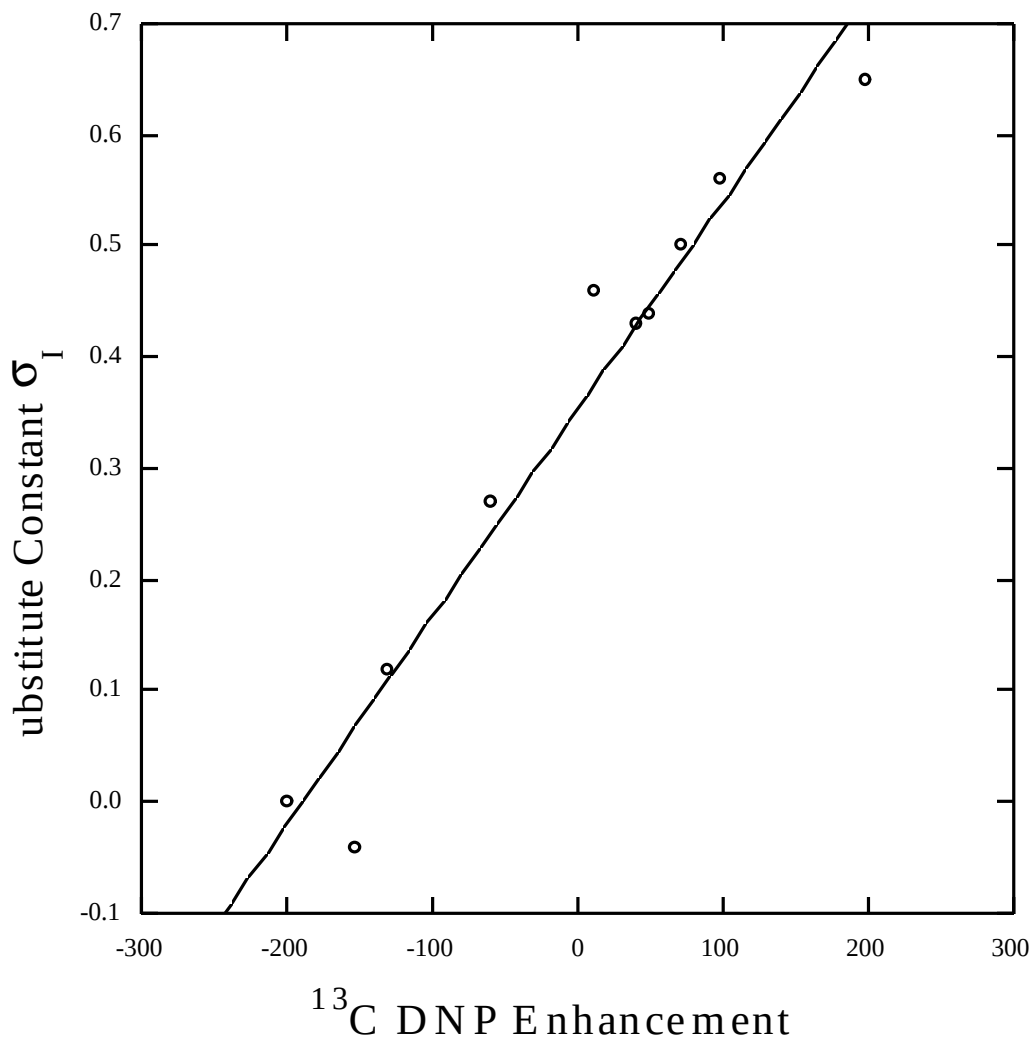


Figure 4.3. Meta ^{13}C DNP Enhancements as a Function of the Hammett σ_I Constant (from the comprehensive data given by Exner[54])

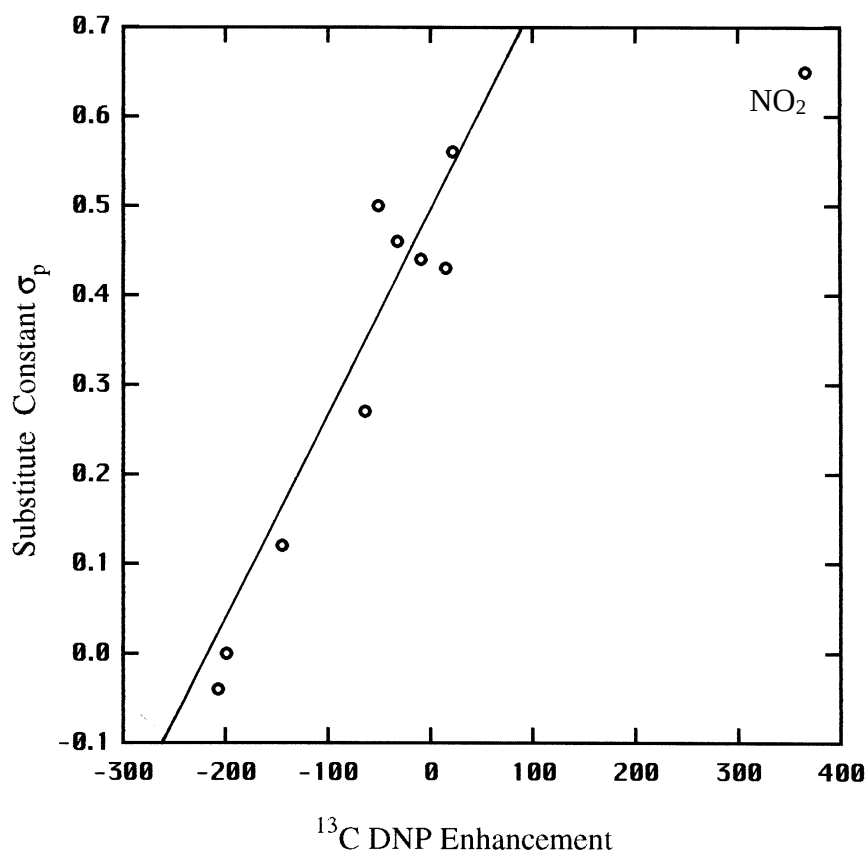


Figure 4.4. Para ^{13}C DNP enhancements as a Function of the Hammett σ_I
(from the comprehensive data given by Exner[54])

4.4, a better correlation was obtained for both of the meta and para positions with correlation coefficients, 0.9726 and 0.9554-(NO₂ data not including), respectively. A large deviation is observed for nitrobenzene. This may be due to that the ^{13}C DNP enhancement data for nitrobenzene was measured at different experimental conditions. As has been mentioned, the inductive parameter σ_I is an operational measure of the non-resonance effects. The results suggest that in the ground state of these molecules the inductive effect is much more important than resonance effect in terms of the electronic charge distribution on the benzene ring and corresponding correlation with ^{13}C DNP enhancements.

The ^{13}C DNP A_∞ enhancements at the ortho (C-2) position are spread over a magnitude of more than 700, with extreme values for nitrobenzene and benzene. Since the ortho substituents are bound to the adjacent position, proximity effects such as steric effects, which are less significant at other positions, could play a significant role at the ortho position. To date, no Hammett kinds of correlation are observed in chemical reactions. The plot of ortho ^{13}C DNP enhancements verses Hammett inductive constants shows a good correlation with correlation coefficient 0.9462(NO_2 data not including, see Fig.4.5). A large deviation is also observed for nitrobenzene. This may due to the same reason as mentioned above.

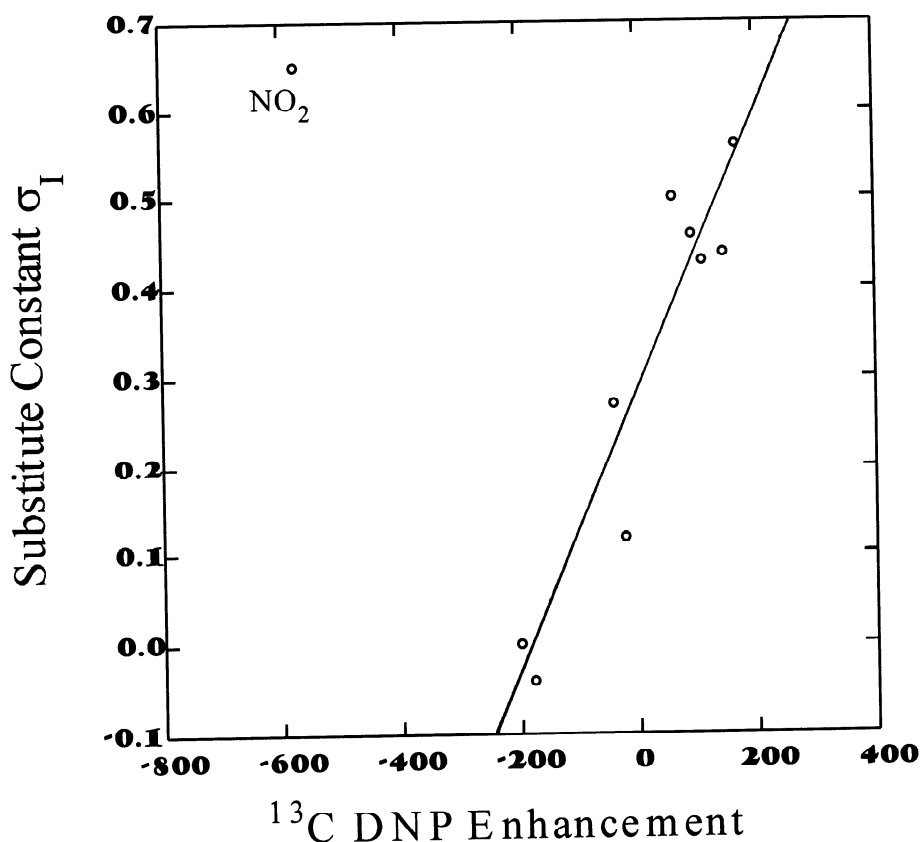


Figure 4.5. Ortho ^{13}C DNP Enhancements as a Function of the Hammett σ_I
(from the comprehensive data given by Exner[54])

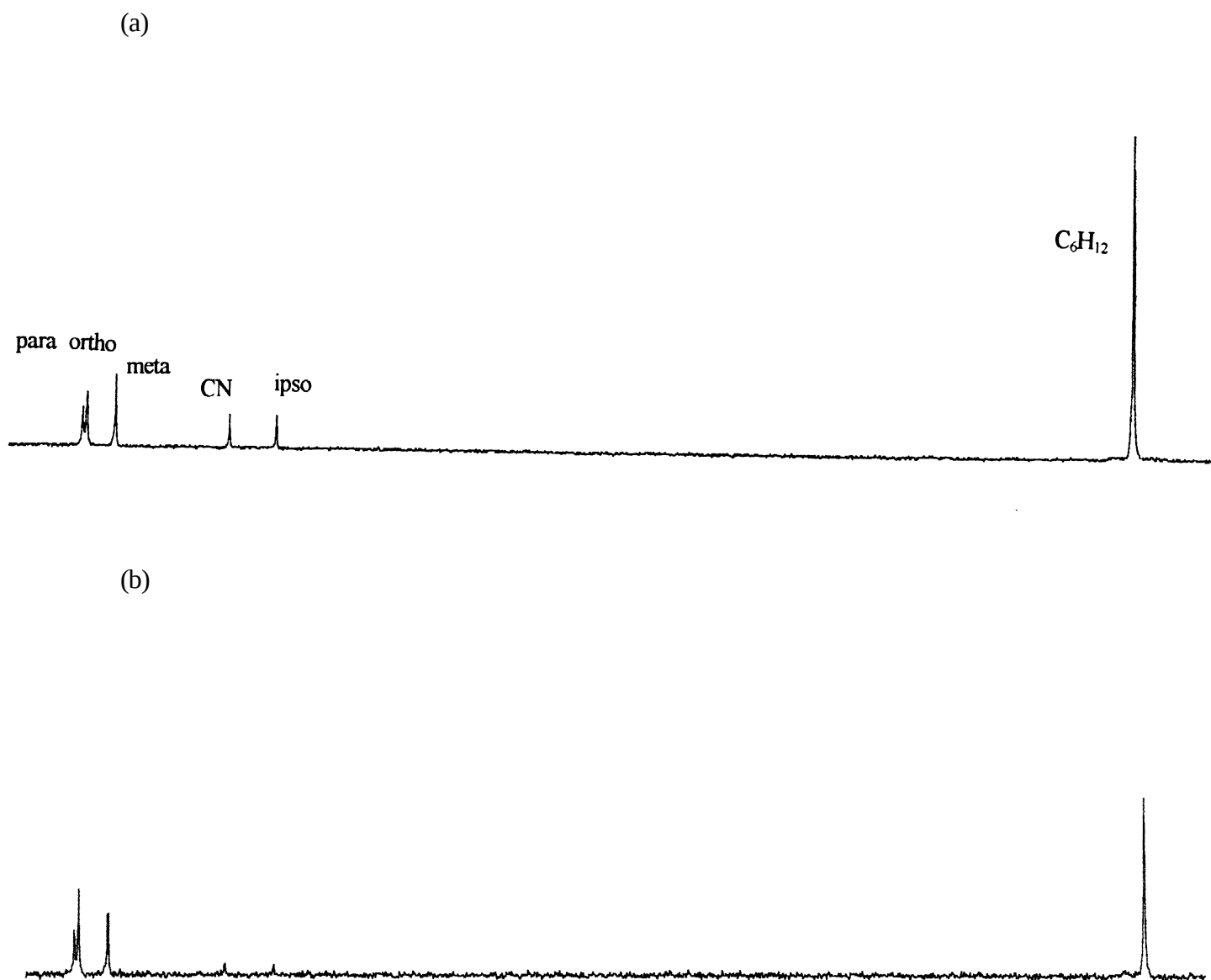
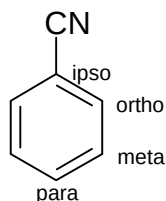


Figure 4.6 LLIT ^{13}C DNP Spectrum (50.1 MHz) for 50/50 (v/v) % Benzonitrile/Cyclohexane with 0.1 M TEMPO: (a) static NMR Spectrum (360 scans); (b) Flow DNP Spectrum (360 scans).

Table 4.3. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50 (v/v) % Benzonitrile/Cyclohexane with 0.1 M TEMPO

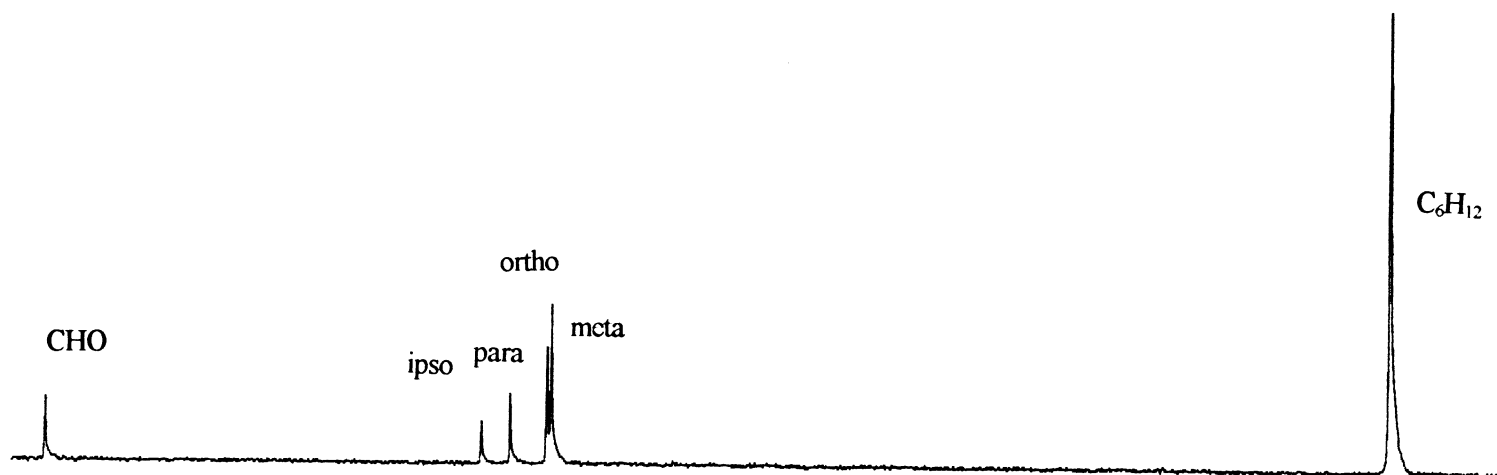
Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipsso	112.95	24.3	2.89	0.881	-281
Ortho	132.08	16.8	1.46	0.913	171
Meta	129.23	25.5	1.11	0.957	98
Para	132.52	37.4	1.42	0.962	22
-CN	117.70	49.9	1.92	0.962	-204



Note:

- (a) Ratio method was used to calculate the ultimate DNP enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

(a)



(b)

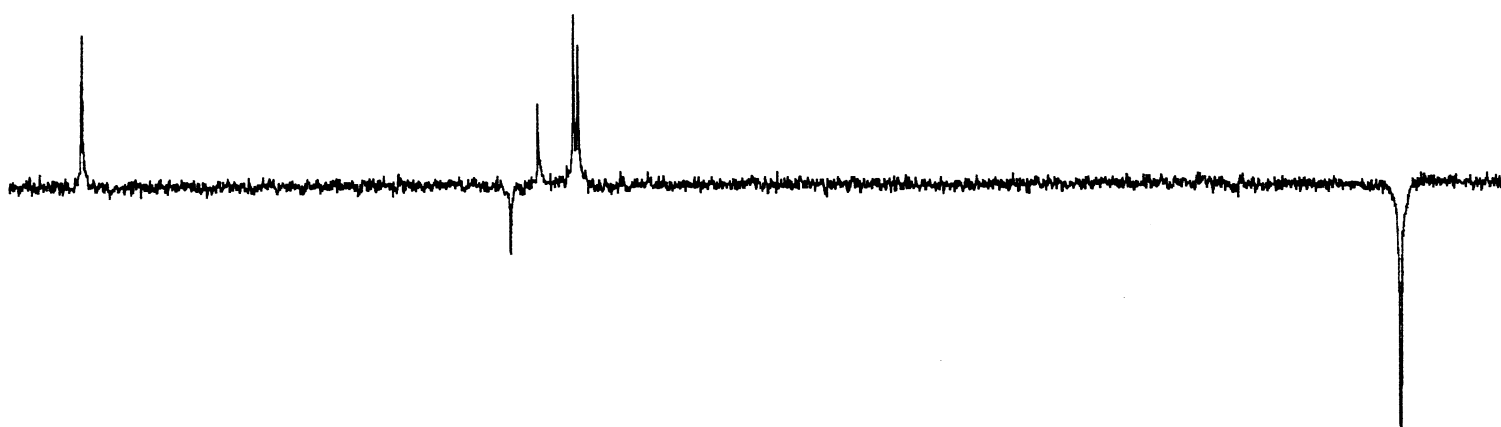
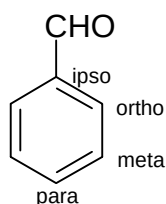


Figure 4.7 LLIT ^{13}C DNP Spectrum (50.1 MHz) for 20/80 (v/v) % Benzaldehyde/Cyclohexane with 0.1 M TEMPO: (a) static NMR Spectrum (3000 scans); (b) Flow DNP Spectrum (735 scans).

Table 4.4. LLIT ^{13}C DNP Relaxation and Enhancement Data for 20/80 (v/v) % Benzaldehyde/Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipsso	136.97	32.0	1.15	0.963	-456
Ortho	129.38	20.1	1.46	0.943	131
Meta	128.79	13.7	1.38	0.899	93
Para	133.83	14.0	1.23	0.912	78
-CHO	190.69	22.8	1.21	0.947	373



Note:

- Ratio method was used to calculate the DNP ultimate enhancements.
- ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

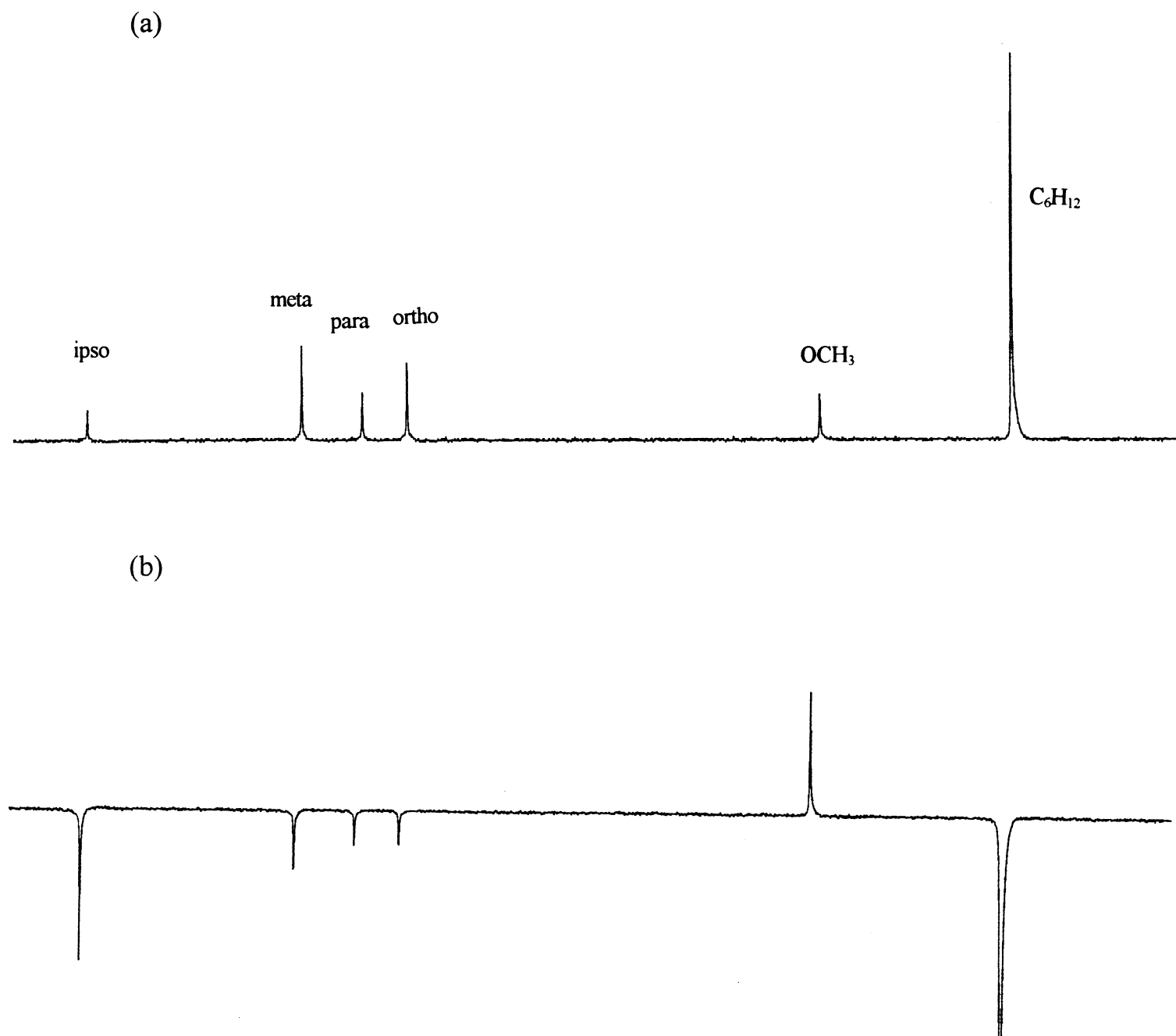
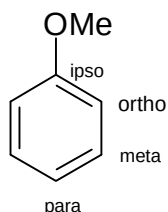


Figure 4.8 LLIT ^{13}C DNP Spectrum (50.1 MHz) for 20/80 (v/v) % Anisole/Cyclohexane with 0.1 M TEMPO: (a) static NMR Spectrum (1357 scans); (b) Flow DNP Spectrum (620 scans).

Table 4.5. LLIT ^{13}C DNP Relaxation and Enhancement Data for 20/80 (v/v) % Anisole/Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipsso	159.67	30.1	3.13	0.896	-457
Ortho	113.61	18.4	2.49	0.864	-42
Meta	128.94	39.6	2.57	0.935	-61
Para	120.18	18.3	1.83	0.900	-64
-OCH ₃	54.42	8.6	1.47	0.830	266



Note:

- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

4.2. ^{13}C DNP Enhancements study of Monosubstituted Halobenzenes

4.2.1 Introduction

The importance of scalar coupling at adjacent nuclei by the presence of halogen nuclei in the same molecule is a well known phenomenon in the DNP studies. Most of these studies have involved phosphorous and phosphoalkane. For example, ^{31}P in POCl_3 [40], in phosphonitrilic chlorides $((\text{PNCl}_2)_n)_{n=3\sim 7}$ [41], in $\text{C}_6\text{H}_5\text{PCl}_2$ and $\text{C}_6\text{H}_5\text{POCl}_2$ [42], ^{13}C in CCl_4 [43,44], and ^{19}F in cyclic chlorofluoroalkanes [45]. Two possible mechanisms have been postulated. The first one involves an indirect participation mechanism in which adjacent halogen atoms may affect the electronic environment at the nuclei of interest and thus enhancing the scalar enhancement. Bates has reported [46] ^{19}F DNP studies of CFCl_3 and CFCl_2H at 75 G with the free radical di-*t*-butylnitroxide (DTBN). Bates found an abnormal aliphatic fluorine scalar relaxation rate for these two compounds. Limited delocalization of the unpaired electron to the solvent molecule during transient complex formation would account for the high scalar component for CFCl_2H -DTBN, because the nitroxide-proton interaction due to hydrogen bonding is known to be very strong [47-49]. However, this mechanism cannot be used to explain the case of CFCl_3 . In a second mechanism, it is suggested that chlorine promotes the scalar polarization. Thus the polarizable chlorine electrons transmit unpaired electron density from the radical to the fluorine nucleus. This second possible mechanism is the “direct participation mechanism” in which the polarizable halogen electrons may transmit unpaired electron density from the free radical to other nuclei, where the halogen atom acting as a spin messenger. Franklin studied [50] ^{19}F DNP of a series of fluorochloroethanes and two fluorobromoethanes with the free radical bis(diphenylene) phenylallyl (BDPA) and galvinoxyl (GALV). The 1,2-dibromotetrafluoroethane is of interest because the role of the bromine atom can be compared with that of chlorine atoms in the previous study [50]. If the scalar coupling component were generated through the direct mechanism involving transmission of spin information from the easily polarized chlorine atom to the fluorine atom, the more polarizable bromine atom would promote greater polarization of the fluorine atom. However the ^{19}F DNP results showed that fluorochloroethanes have a larger scalar component than fluorobromoethanes. The explanation for this result is that the steric effects for the $\text{C}_2\text{Br}_2\text{F}_4$

may decrease the effectiveness of this mechanism. Over all, a consistent view of the mechanism for halogen participation remains unclear.

The objective of the present work is to further study the halogens involved electron density transfer mechanism by examination of the monosubstituted halobenzenes.

4.2.2. Results and Discussion

Four mono-substituted halobenzenes were examined in this study. In comparison with the ^{19}F DNP study of aliphatic compounds, the ^{13}C DNP study of these halobenzenes have certain advantages: 1) no protons are attached to the carbon bearing the halogen substituent, thus, the indirect mechanism is avoided, 2) there is minimum steric hindrance which prevents the halogen-radical interaction, thus, the steric effect is also small for ^{13}C in the mono-substituted benzene. Figure 4.10-4.12 present the LLIT ^{13}C DNP spectra for fluorobenzene, chlorobenzene and iodobenzene. The ^{13}C DNP data are listed in Table 4.7-4.9 and the ^{13}C DNP enhancement data are summarized in the Table 4.6.

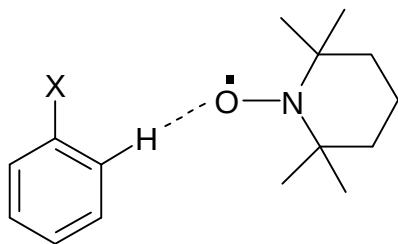
It can be seen that the scalar enhancement for ipso carbon increases in the order of $\text{I} > \text{Br} > \text{Cl} > \text{F}$. It should be mentioned that this is the first observation of a positive scalar

Table 4.6. ^{13}C DNP Enhancement (A_∞) Summary of Four Monosubstituted Halobenzenes

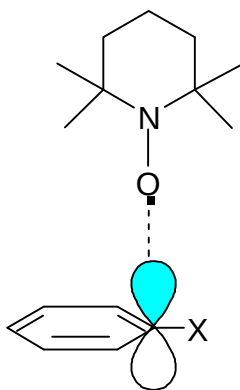
Compound	Ipsa	Ortho	Meta	Para
$\text{C}_6\text{H}_5\text{F}$	-572	63	71	-51
$\text{C}_6\text{H}_5\text{Cl}$	-478	95	11	-32
$\text{C}_6\text{H}_5\text{Br}$	-170	147	50	-9
$\text{C}_6\text{H}_5\text{I}$	478	111	39	15

dominated enhancement observed at the C-1 position in a monosubstituted benzene. Three different mechanisms may lead to the scalar enhancement: 1) The hydrogen bonding interaction at ortho hydrogen atom, 2) the radical directly interacts with C_j and 3) polarizable halogen electrons transmit the unpaired electron density from the free radical to the carbon atom of interest. Figure 4.9 a. b. c. illustrates these three possible mechanisms[9,10,56].

(a)



(b)



(c)

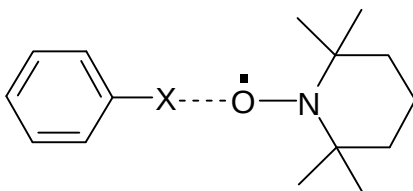


Figure 4.9 Possible Electron Density Transfer Mechanisms

Since the fluorine atom has the strongest electron withdrawing-effect among the halogens, it can be expected that the strongest hydrogen bonding or more acidic C_{ortho}-H bond would form for the fluorobenzene case. This assumes that the scalar enhancement for the ipso carbon (C-1) is caused by hydrogen bonding for the hydrogen at the ortho position, fluorine substitution should lead to the largest scalar enhancement. However the observed ipso ¹³C scalar DNP enhancements are in the order of I > Br > Cl > F. Therefore the hydrogen bonding interaction is apparently not the dominate contribution to the scalar enhancement. If the TEMPO radical direct interaction with the C_j carbon atom of the substrate is important. The largest scalar enhancement should be observed for fluorobenzene. This is because: 1) the C_j in fluorobenzene has lower electron density than the other halobenzenes, this will promote the electron density transfer from free radical to the carbon and 2) fluorine has the smallest steric hindrance for the interaction between TEMPO radical and the C_j site than with other halogen atom substituted substrates. However this expectation is contrary to the experimental results. Thus, it appears that the radical direct interaction with C_j is not responsible for the scalar enhancement of C_j.

It follows from the above discussion that the scalar enhancement for C_j in halobenzenes is caused by specific interactions between the halogen atom and the free radical. In addition, the polarizable ability of the halogen atoms is in the order of I > Br > Cl > F. This trend is consistent with the C_j scalar enhancement results. This suggests that the facile transfer of spin polarization to carbon via the highly polarizable halogen atoms is possible and the dominate electron transfer mechanism for this system.

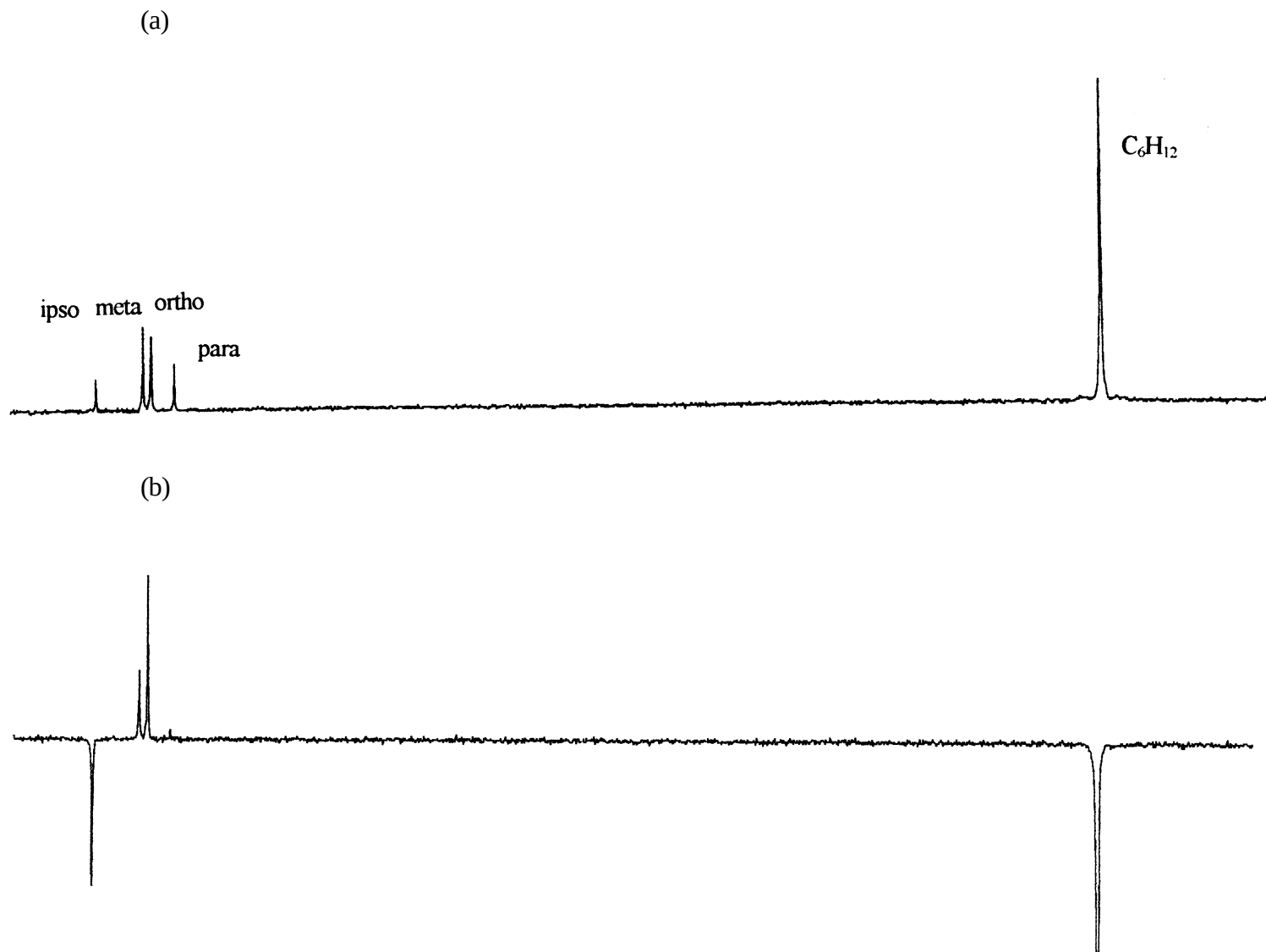
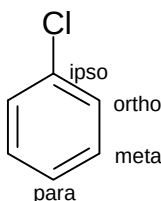


Figure 4.10 LLIT ^{13}C DNP Spectrum (50.1 MHz) for 50/50 (v/v) % Chlorobenzene/Cyclohexane with 0.1 M TEMPO: (a) static NMR Spectrum (360 scans); (b) Flow DNP Spectrum (360 scans).

Table 4.7. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50 (v/v) % Chlorobenzene/Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipso	134.41	41.5	1.90	0.954	-478
Ortho	128.50	18.4	1.92	0.895	95
Meta	129.37	13.8	2.30	0.833	11
Para	126.02	15.1	1.73	0.885	-32



Note:

- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

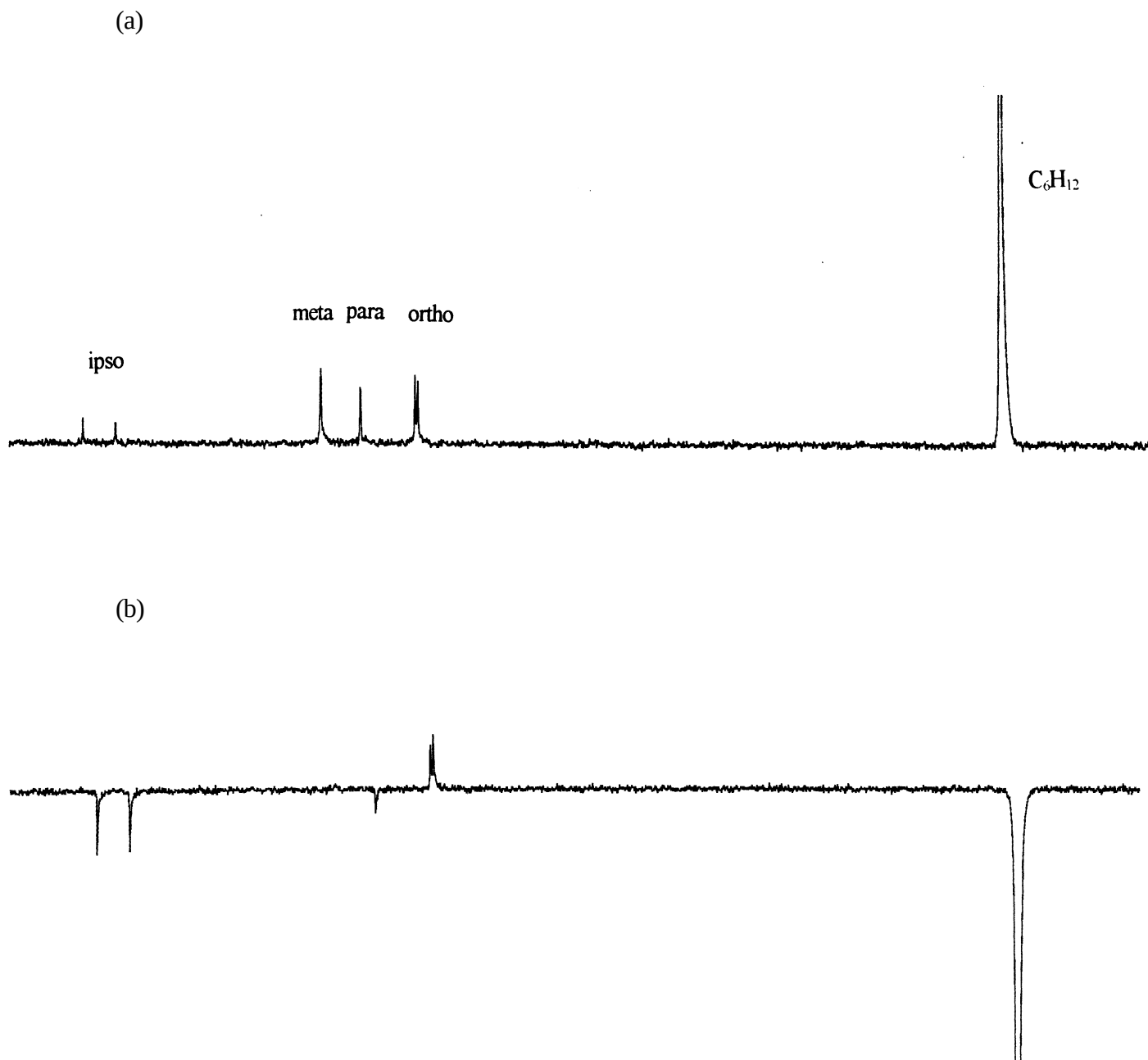
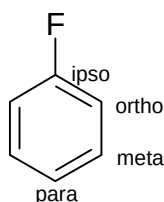


Figure 4.11. LLIT ^{13}C DNP Spectrum (50.1 MHz) for 50/50 (v/v) % Fluorobenzene/Cyclohexane with 0.1 M TEMPO: (a) static NMR Spectrum (3800 scans); (b) Flow DNP Spectrum (2000 scans).

Table 4.8. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50 (v/v) % Fluorobenzene/Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipso	165.43	27.3	2.26	0.917	-572
Ortho	115.22	14.8	1.47	0.901	63
Meta	129.45	25.9	1.48	0.943	71
Para	123.47	13.5	1.51	0.888	-51



Note:

- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

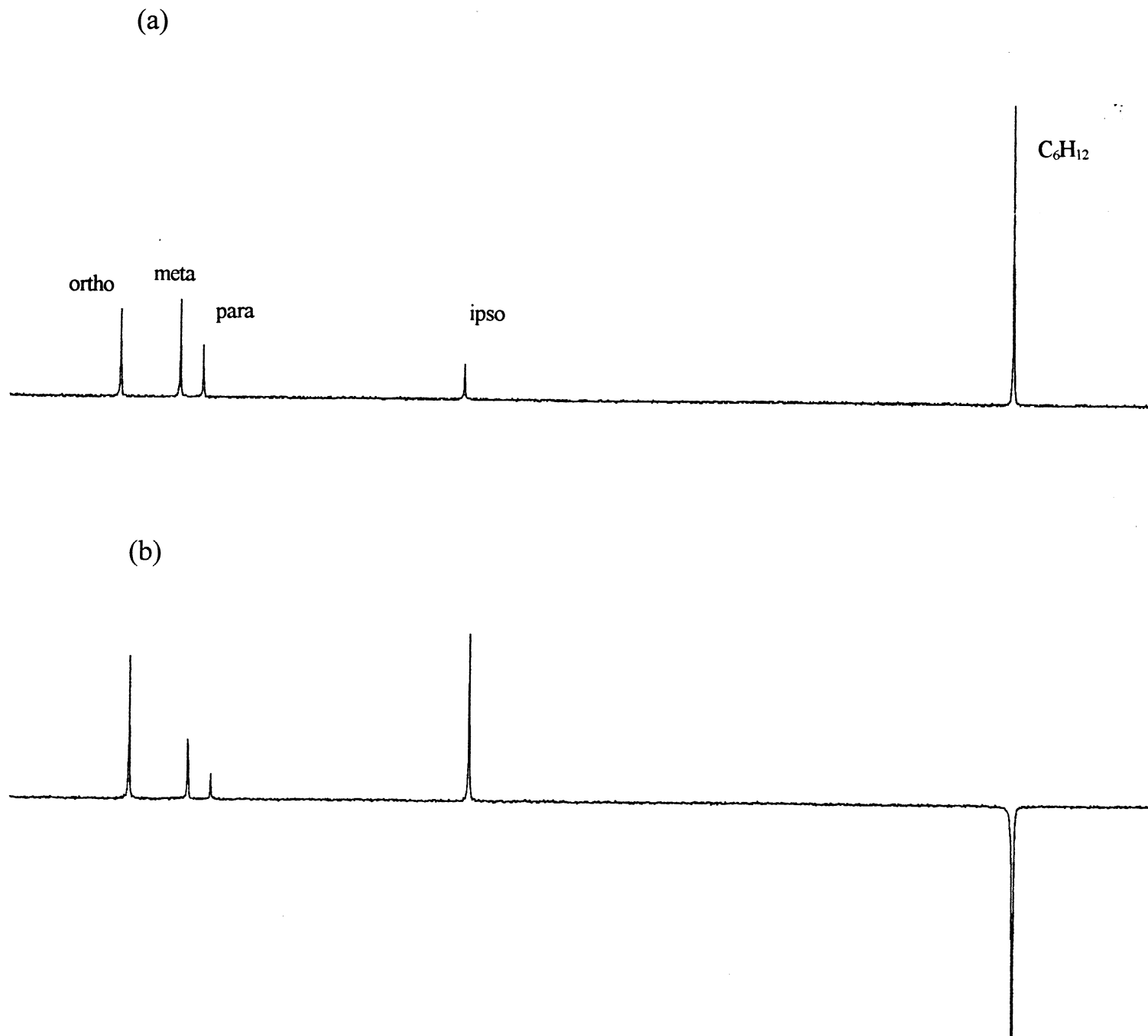
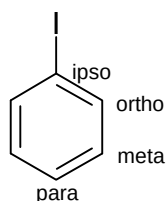


Figure 4.12. LLIT ^{13}C DNP Spectrum (50.1 MHz) for 50/50 (v/v) % Iodobenzene/Cyclohexane with 0.1 M TEMPO: (a) static NMR Spectrum (540 scans); (b) Flow DNP Spectrum (360 scans).

Table 4.9. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50 (v/v) % Iodobenzene/Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipso	94.78	19.9	0.96	0.952	478
Ortho	137.48	10.5	1.12	0.894	111
Meta	130.11	11.0	0.95	0.914	39
Para	127.26	9.3	0.987	0.894	15



Note:

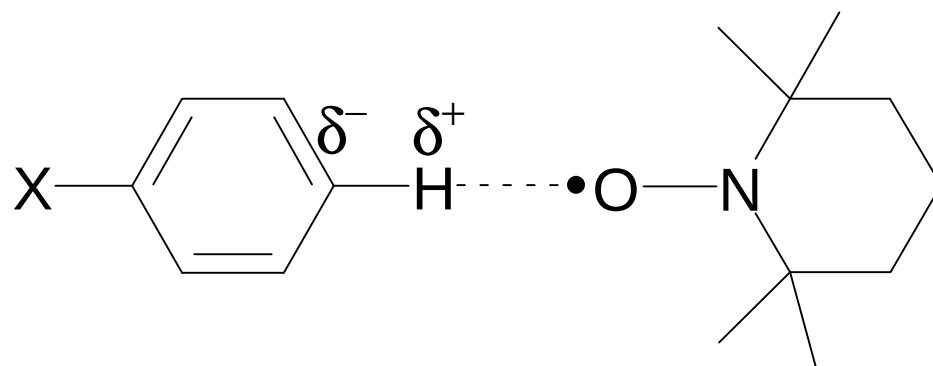
- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

4.3. Solution ^{13}C DNP Studies of Possible Polarization Mechanism via Abundant ^1H Spin in the Mono-substituted Aromatic Compounds

4.3.1. Introduction

Previous work has demonstrated that the DNP technique provides a potentially powerful tool for the investigation of the interaction between various molecules and free radicals. The study of DNP enhancements can provide direct information on the mechanism of electron spin density transfer from the free radical (electron donor) to the sample molecules (electron acceptor). Several possible transfer models have been proposed (see Fig. 4.12). One is the indirect polarization model[9]. In this model, it is believed that the formation of the weak hydrogen bond between TEMPO free radical and the proton attached to carbon plays an important role. For example[9], Tsai and coworkers have studied the ^{13}C DNP of the chlorobenzene, they found that C-1 carbon exhibits a large negative dipolar dominated enhancement, whereas, the C-2 carbon exhibits a large scalar dominated enhancement. The large positive scalar enhancement for C-2 carbon comes from the possible weak complexation of free radical TEMPO with the proton attached to C-2. The electron withdrawing chlorine atom causes the enhanced proton donor capability of the C-2 aromatic proton in comparison with benzene proton. The large dipolar dominated enhancement for ipso carbon (C-1) is probably due to a smaller scalar contribution and lack of three-spin effects[9]. The second model is direct spin density delocalization model[10]. In this model, the positive electron spin density from TEMPO is transmitted into the anti-bonding orbital π^* of the aromatic molecule. The transmitted electron spin density correlates with the σ orbitals around the carbon nuclear and induces an excess positive electron spin density near the carbon-nucleus and excess negative spin densities at the adjacent carbon nuclei and the hydrogen nucleus.[37] A schematic illustration for these two mechanism are shown in Figure 4.13 (a) and (b), respectively.

(a)



(b)

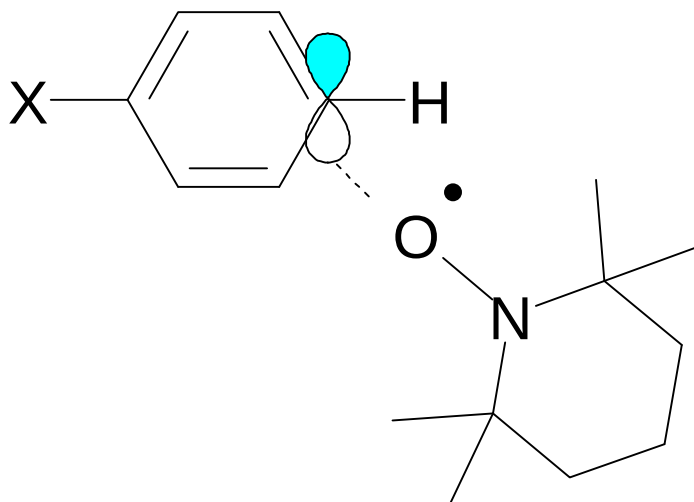


Figure 4.13. Possible Mechanism for ^{13}C DNP enhancements

Besides these mechanisms, is it possible that still have some other models. For example, it is also possible that the electron spins provide diffusion via abundant proton spins from one proton to another by mutual spin flips and finally transfer the polarization to the carbon nucleus. A schematic illustration diagram for this possible transfer model is shown in Figure 4.14.

In order to examine the possible importance of this possible spin transfer model, a simple experiment was designed.

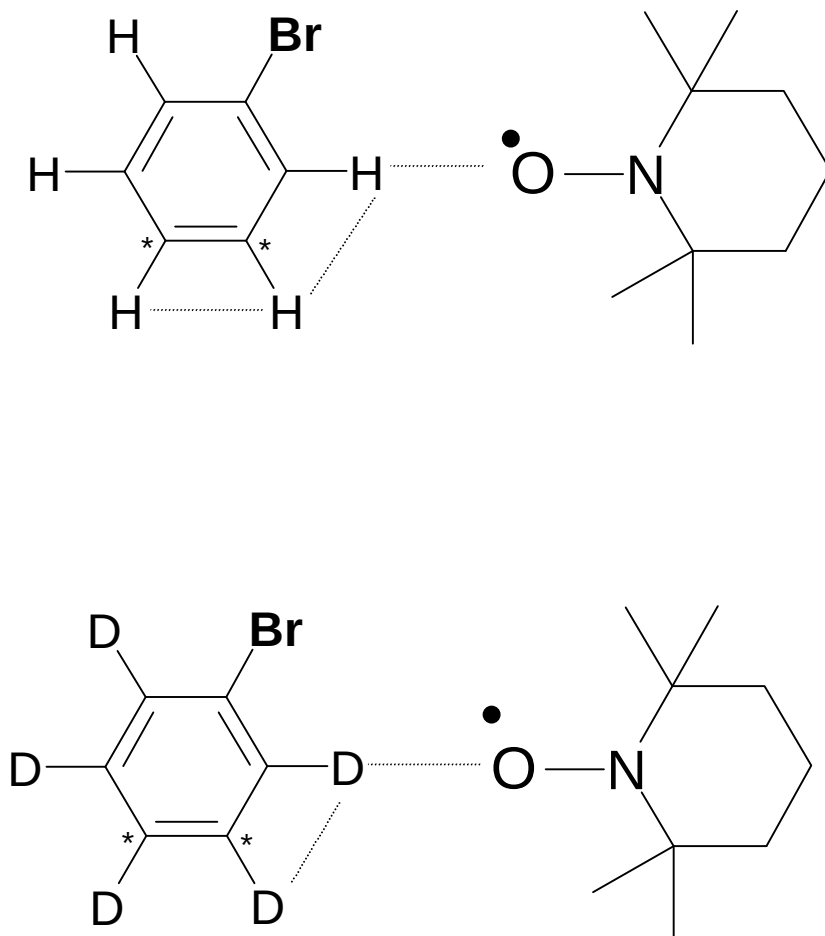


Figure 4.14 Polarization Transfer Mechanism Models
(Via Abundant ^1H Spins and Mutual Hydrogen Spin Flips)

4.3.2. Experimental Results and Discussion

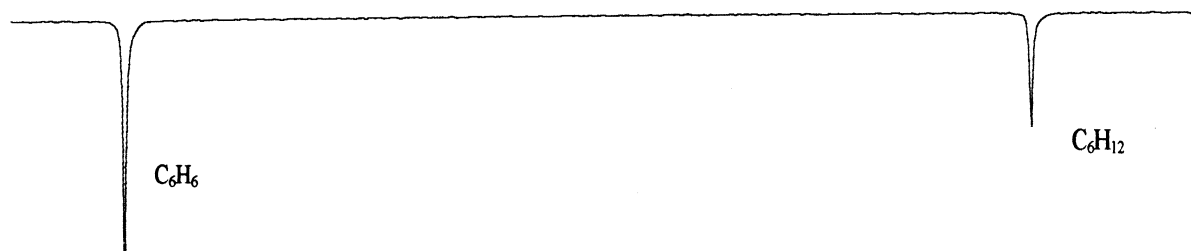
Deuterium can be easily incorporated into molecules and has been commonly used in the studies of mechanistic and structure information. In comparison with the proton, the deuterium nuclide has low magnetogyric ratio and quadrupole moment ($I=1$). Since the proton has only half the mass of the deuteron, the deuteron is less polarizable than the proton. Previous deuterium DNP studies^{9,39} shown that the radical-deuteron coupling is very inefficient even at very high radical concentrations. Thus, polarization transfer from one site to another via mutual hydrogen spin flips is suppressed for the deuterated examples. Based on the above difference between the proton and deuteron, polarization transfer via the abundant proton spins to the carbon-13, a significant difference between ^{13}C DNP enhancement of the deuterium substituted species and their protonated analogs should be expected. The ^{13}C DNP enhancement of Benzene- d_6 , Toluene- d_8 , Bromobenzene- d_5 and their protonated species were measured at the same conditions as the respective hydrogen compounds. The ^{13}C DNP spectra are shown in **Figure 4.15.- 4.17**. The ^{13}C DNP results are shown in **Table 4.11-4.15**. The ultimate enhancements are summarized in **Table 4.10**.

Table 4.10. ^{13}C DNP Enhancement (A_∞) Summary of Three Monosubstituted benzenes and Their Deuteron Analogs

Compound	C-X	Ortho	Meta	Para	Other
Benzene	-199	-199	-199	-199	
Benzene- d_6	-205	-205	-205	-205	
Bromobenzene	-107	147	50	-9	
Bromobenzene- d_6	-167	102	9	-49	
Toluene	-562	-179	-153	-207	-187
Toluene- d_6	-487	-218	-238	-221	-214

The results for ^{13}C DNP enhancements in Table 4.6 exhibit no significant differences between deuterium species and their protonated analogs. This indicates that the polarization transfer via mutual hydrogen spin flips via the abundant proton spins to the carbon of interest is not important. The ^{13}C DNP results also show that the DNP enhancements, at all positions, are slightly more negative in the deuterium case than in the protonated case. The increasing dipolar dominated enhancements is probably due to the lack of three-spin effects and a smaller scalar contribution in the deuterium case. From Equation 2.41, it is easy to understand that the low magnetogyric ratio of deuterium will decrease the three-spin effects. The smaller scalar contribution could also arise from the fact that the deuterium is a slightly stronger electron donating atom than the proton. This makes all carbon sites less favorable for the scalar interaction.

(a)



(b)

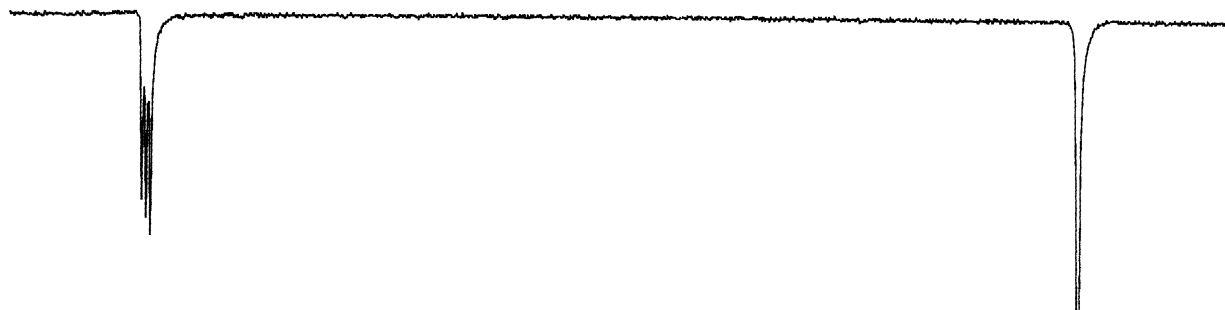


Figure 4.15 LLIT ^{13}C DNP Spectrum (50.1 MHz) for (a) 60/40 (v/v) % Benzene/Cyclohexane with 0.1 M TEMPO (32 scans); (b) 40/30 (v/v) % Benzene- d_6 /Cyclohexane with 0.1 M TEMPO (64 scans).

Table 4.11. LLIT ^{13}C DNP Relaxation and Enhancement Data for 60/40 (v/v) % Benzene/Cyclohexane and 40/30 (v/v) % Benzene- d_6 /Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Benzene	128.24	29.3	1.78	0.939	-199
Benzeze- d_6	127.52	49.5	2.10	0.958	-205

Note:

- (a) Exhaustive method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

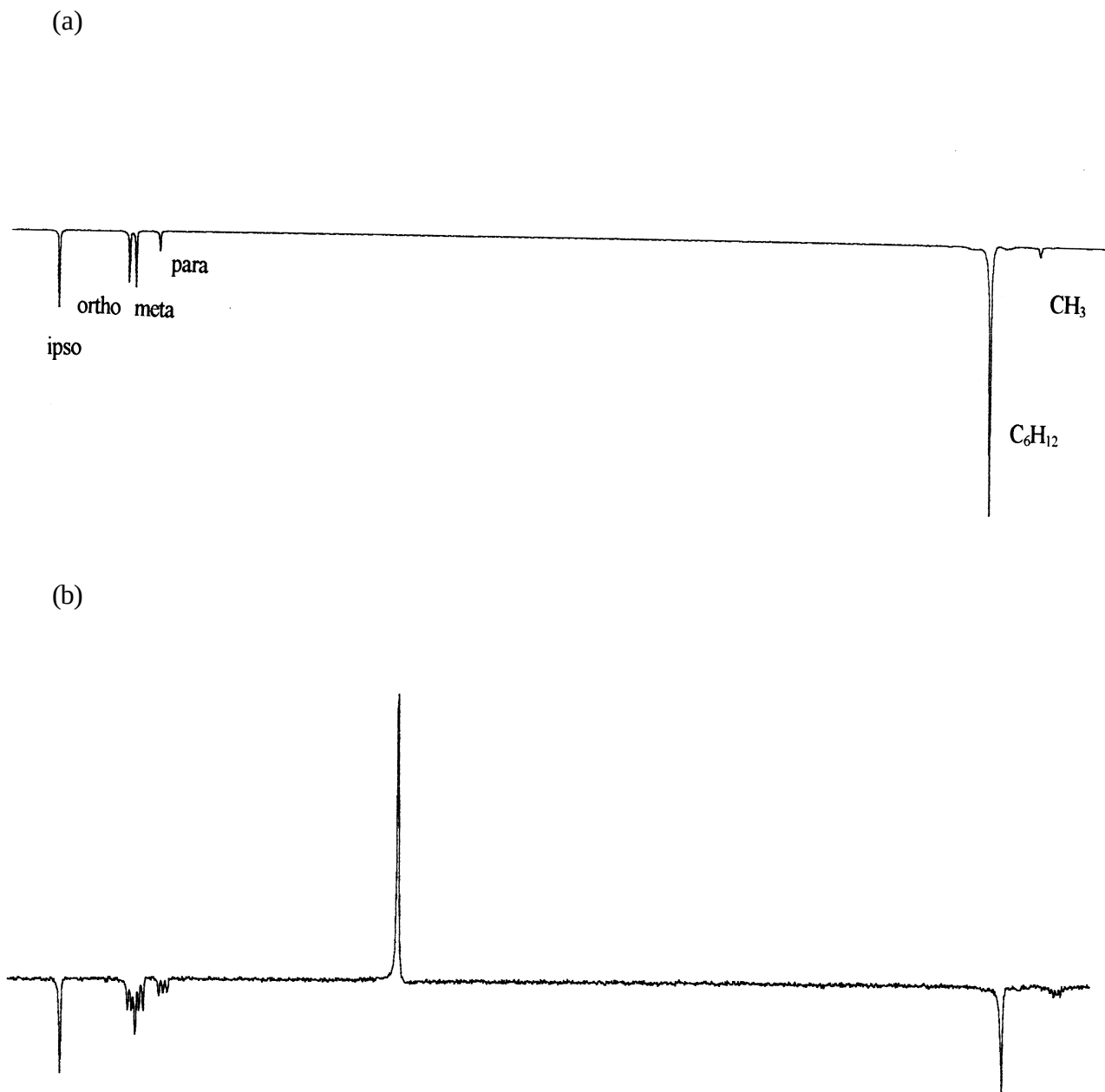
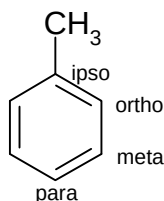


Figure 4.16 LLIT ^{13}C DNP Spectrum (50.1 MHz) for (a) 50/50 (v/v) % Toluene/Cyclohexane with 0.1 M TEMPO (360 scans); (b) 50/50/10 (v/v) % Toluene- d_6 / CCl_4 /Cyclohexane with 0.1 M TEMPO (360 scans).

Table 4.12. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50 (v/v) % Toluene/Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipsso	137.03	58	3.20	0.944	-562
Ortho	128.73	20	2.83	0.859	-179
Meta	127.94	21	2.82	0.866	-153
Para	125.14	15	2.88	0.808	-207
-CH ₃	21.02	16.3	2.19	0.865	-187

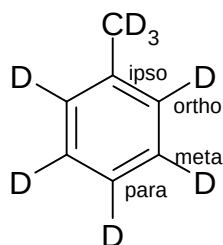


Note:

- Ratio method was used to calculate the DNP ultimate enhancements.
- ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

Table 4.13. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50 (v/v) % Toluene- d_8 /Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipso	136.79	63.8	3.44	0.946	-487
Ortho	128.45	54.1	2.80	0.948	-218
Meta	127.58	41.1	3.17	0.923	-238
Para	124.78	56.6	2.70	0.952	-221
-CD ₃	20.46	26.8	2.43	0.909	-214



Note:

- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

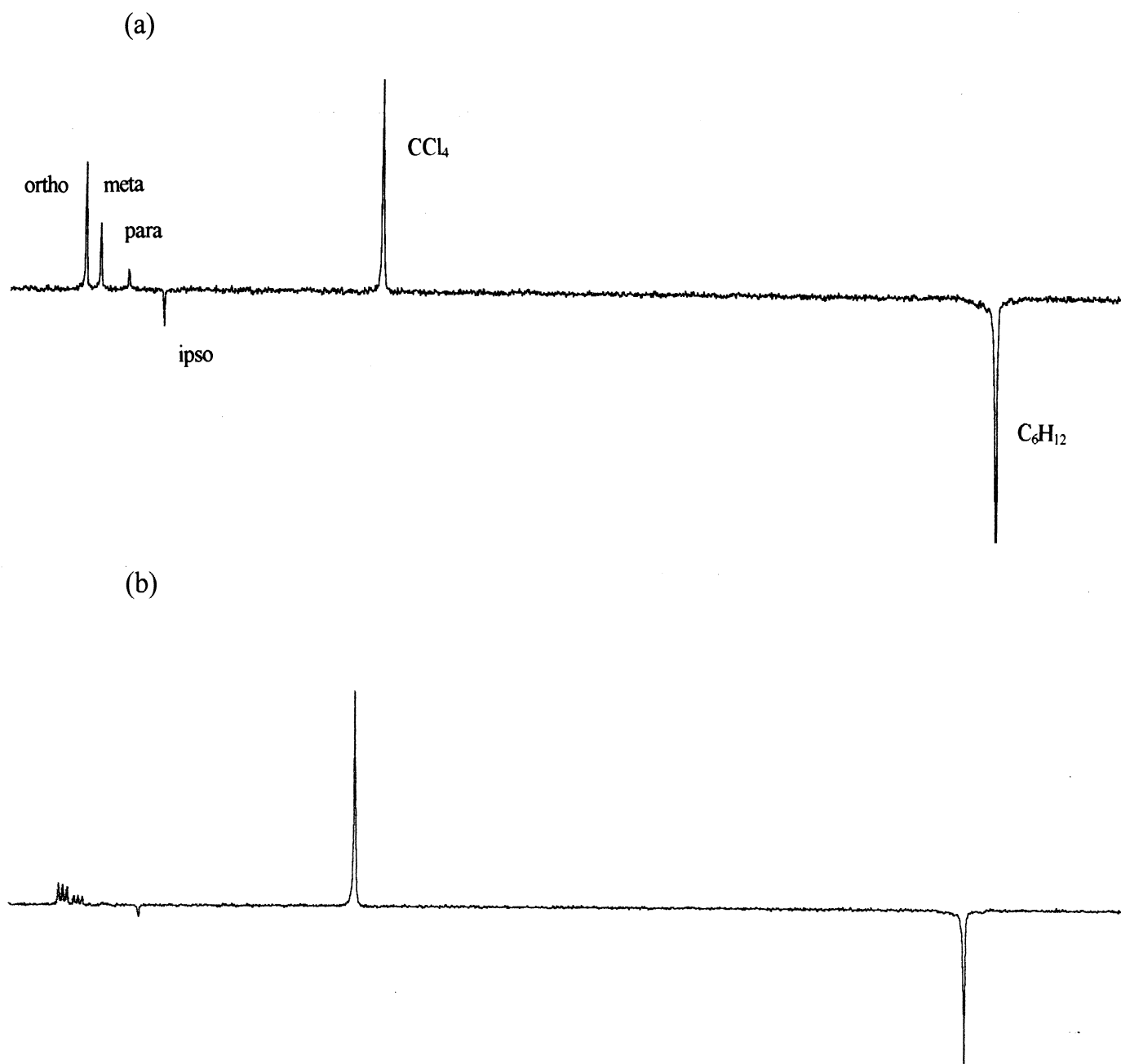
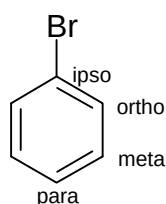


Figure 4.17 LLIT ¹³C DNP Spectrum (50.1 MHz) for (a) 50/50/10 (v/v) % Bromobenzene/CCl₄/Cyclohexane with 0.1 M TEMPO (420 scans); (b) 50/50/10 (v/v) % Bromobenzene-d₅/CCl₄/Cyclohexane with 0.1 M TEMPO (1280 scans).

Table 4.14. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50/10 (v/v) % Bromobenzene/ CCl_4 /Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipsso	122.52	13.5	2.13	0.841	-167
Ortho	131.49	20.0	1.40	0.930	147
Meta	129.82	17.7	1.40	0.921	50
Para	126.53	14.8	1.55	0.895	-9

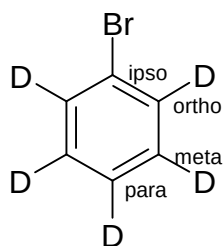


Note:

- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

Table 4.15. LLIT ^{13}C DNP Relaxation and Enhancement Data for 50/50/10 (v/v) % Bromobenzene- d_5 / CCl_4 /Cyclohexane with 0.1 M TEMPO

Carbon Type	Peak ^b Position (ppm)	T_{10} ^c (Sec.)	T_1 ^c (Sec.)	f ^d	A_∞ ^{a,e,f,g}
Ipsso	122.30	15.0	1.56	0.896	-167
Ortho	131.06	35.2	1.47	0.958	102
Meta	129.23	35.9	1.65	0.954	9
Para	126.02	29.3	1.81	0.938	-49



Note:

- (a) Ratio method was used to calculate the DNP ultimate enhancements.
- (b) ^1H broad-band decoupling was employed to eliminate proton-carbon coupling.
- (c) T_1 and T_{10} are the spin-lattice relaxation times of the carbon nuclei with and without TEMPO in the sample solution, respectively.
- (d) The leakage factor f was calculated based on T_1 measurements at 4.7 T magnetic field.
- (e) The 0.33 T ^{13}C DNP enhancements were monitored at 4.7 T. All data was obtained at room temperature.
- (f) Cyclohexane was used as the reference compound with $A_\infty = -270 \pm 40$.
- (g) The ultimate ^{13}C DNP enhancement A_∞ is an average value of four measurements at different power levels. The estimated relative standard deviation for A_∞ is about 15%.

CHAPTER 5. CONCLUSIONS

The ^{13}C DNP studies of over ten monosubstituted aromatic compounds with electron withdrawing and donating functional groups indicate that transient bonding is an important way to transmit electron spin density from the free radical to the carbon nuclei of organic molecules. The ^{13}C DNP results for the aromatic molecules also show that the ^{13}C DNP technique is sensitive to the electronic environment of the substituted benzene ring. The ^{13}C DNP enhancements results also show that ortho, meta and para position exhibit large scalar dominated enhancements for compounds with electron-withdrawing groups (F, Cl, Br, I, CN, CHO, NO_2). Whereas, the dipolar dominated enhancements are observed in compounds with electron donating substituted groups (OCH_3 , CH_3 , NH_2). The ^{13}C DNP results also show that larger magnitude scalar enhancements for most compounds follow the order of ortho > meta > para. These results indicate that the ^{13}C DNP enhancement have a definitive relationship with substituent electronic effects. The results of correlation studies of ^{13}C DNP enhancements with the Hammett σ constants suggest that in the ground state of these aromatic molecules the inductive effect is much more important than resonance effect in terms of the electronic charge distribution on the benzene ring.

The large scalar dominated enhancement (478) obtained at ipso carbon of iodobenzene indicates that the facile transfer of spin polarization to carbon via the highly polarizable halogen atoms is possible and the dominated electron transfer mechanism for this system.

The results for ^{13}C DNP enhancements of bromobenzene, benzene, toluene and their deuterium species exhibit no significant differences. This indicates that the polarization transfer via mutual hydrogen spin flips via the abundant proton spins to the carbon of

interest is not important. . The ^{13}C DNP results also show that the DNP enhancements, at all positions, are slightly more negative in the deuteron case than in the protonated case. The increasing dipolar dominated enhancements is probably due to the lack of three-spin effects and a smaller scalar contribution in the deuteron case.

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