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1.¹³C NMR SPECTROSCOPY

The most abundant isotope of carbon is C-12 (nuclear spin, I = 0) and this is NMR inactive. However, the natural abundance of C-13 or ¹³C is 1.1% and has I = 1/2 like a proton. Therefore, C-13 nuclei are **NMR active**. Unfortunately, the resonances of ¹³C nuclei are more difficult to observe than those of protons (¹H) due to low magnetogyric ratio (γ) (it is 1/4th of the proton) and low natural abundance. Therefore, ¹³C nuclei are very less sensitive and overall sensitivity is about $\frac{1}{5700}$ of the proton. The advantage of ¹³C NMR over ¹H NMR is that proton NMR gives indirect information about carbon skeleton of the molecule whereas, ¹³C NMR gives direct information because each carbon (if they are not equivalent) of the molecule gives its own signal whether it has any attached hydrogen or not.

Chemical Shift

Generally organic compounds exhibit ¹³C signals in the range of 0-220 ppm (although CH_4 and CH_3I are found at -2.4 and -24.0 ppm respectively. On the other hand, CI_4 signal appears at -293.0 ppm due to heavy atom effect (spin-orbit coupling plays a role in this case).

Nature of Carbon Atom	δ (ppm)
Aliphatics	10-40
С–О, С–Х	50-70
Alkyne	70-80
Alkenes, Aromatics	110-150
RCOOH, RCOOR	170-180
RCHO	190-200
RCOR'	205-220

However, in transition metal complexes, these values can change substantially and extends to more than +400 ppm and M-CH₃ carbon often appears at lower frequency below TMS (= 0 ppm) i.e. highly upfield shifted.

Compounds	δ (ppm)
M-alkyl	below 0
π -bonded M-alkenes	extend up to 100 ppm outside their usual range
and M-arenes	
М-СО	170-290
M-carbenes	250-370



Information from ¹³C NMR

- 1. Number of signals: Tells about different types of carbon atoms present (non-equivalent carbons)
- 2. Position of Signals: Gives information about either carbons are aliphatic, alkene, aromatic, aldehydic, carbene or carbonyl etc.
- 3. Splitting of signals: In proton-coupled ¹³C NMR, splitting of signals gives information of number of hydrogen atoms attached to a particular carbon.



Spin-Spin Splitting in ¹³C NMR

- Because of low natural abundance of ¹³C nuclei, the probability of finding two ¹³C atoms adjacent to each other in the same molecule is very low. Hence, no spin-spin splitting between ¹³C-¹³C nuclei.
- 2. Spin-spin splitting occurs between hydrogen attached to the particular ¹³C atom. Such spectrum called proton coupled ¹³C NMR spectrum. The splitting of ¹³C signal occurs according to n+1 rule. The proton coupled ¹³C NMR spectrum are very difficult to interpret due to large coupling constant (J = 100-320 Hz). ¹H–¹³C ¹J = ~100-320 Hz; ¹H–C–¹³C ²J = 0-60 Hz; ¹H–C–C–¹³C ³J = 0-60 Hz



3. When there is no coupling between ¹H and ¹³C nuclei, then such ¹³C spectrum called as proton decoupled ¹³C NMR spectrum i.e. ¹³C{¹H} NMR spectrum. This gives only singlets and thus simplifies the spectrum. However, this lost the information about attached hydrogens. Majority of ¹³C NMR spectra are obtained as proton decoupled spectra.



¹³C{¹H} NMR spectrum of [Au(CH₃)(carbene)] in CDCl₃.The solvent signals are marked with '*'.

2. NUCLEAR OVERHAUSER EFFECT (NOE)

When we obtain a ${}^{13}C{}^{1}H$ NMR spectrum, the intensities of many of the carbon resonances increase significantly in comparison to the intensities observed in a proton-coupled experiment. Carbon atoms directly attached with hydrogen atoms are enhanced the most, and the enhancement increases (but not always linearly) as more hydrogens are attached to a particular carbon. This effect is known as the

Nuclear Overhauser Effect (NOE) and this is applied to the magnitude of the effect as well as to the phenomenon itself. Thus, NOE is the change in the intensity of the signal of a nucleus upon irradiation of a nearby nucleus and this operates through space. This effect can be either positive or negative, depending on types of atom are involved. In the case of ¹³C interacting with ¹H, the effect is positive; irradiating the hydrogens increases the intensities of the carbon signals.

The magnitude of NOE depends on the balance of relaxation mechanisms, and its maximum value for an A{B} experiment in which the B nucleus is saturated is given by

$$NOE_{max} = \frac{1}{2} \left(\frac{\gamma_{irr}}{\gamma_{obs}} \right)$$

Where, γ_{irr} is the magnetogyric ratio of the irradiated nucleus (B), and γ_{obs} is that of the observed nucleus (A). Remember that NOE_{max} is the *enhancement* of the signal, and it must be added to the original signal strength: Total predicted intensity (maximum) = 1 + NOE_{max}

For a ¹³C{¹H} NMR spectrum, NOE_{max} = $\frac{1}{2} \left(\frac{267.5}{67.28} \right) = 1.988$; indicating that the ¹³C signals can be enhanced up to 200% by irradiation of the hydrogens. Therefore, the total predicted intensity will be three. However, the maximum enhancement is 50% for homonuclear decoupling (e.g. ¹H{¹H}).

In a ¹³C{¹H} NMR spectrum, the total NOE for a given carbon increases as the number of nearby hydrogens increases. Thus, we usually find that the intensities of the signals in a ¹³C spectrum (assuming a single carbon of each type) assume the order: $CH_3 > CH_2 > CH >> C$. Since, magnitude of NOE depends on relaxation mechanism and dipolar relaxation is particularly important for spin-1/2 nuclei and, as the rate is inversely proportional to the sixth power of the distance between the nuclei, it is most significant when the nucleus being irradiated is directly bonded to the one being observed. Therefore, NOE decreases with the 6th power of the distance between the interacting nuclei (NOE is effective typically up to ~4 Å).

Signal enhancement due to NOE is an example of **cross-polarization**, in which a polarization of the spin states in one type of nucleus causes a polarization of the spin states in another nucleus. In a ${}^{13}C{}^{1}H{}$ spectrum, when the hydrogens in the molecule are irradiated, they become saturated and attain a distribution of spins very different from their equilibrium (Boltzmann) state. There are more spins than normal in the *excited* state. Due to the interaction of spin dipoles, the spins of the carbon nuclei "sense" the spin imbalance of the hydrogen nuclei and begin to adjust themselves to a new equilibrium state that has more spins in the *lower* state. This increase of population in the lower spin state of carbon increases intensity of the NMR signal.

The NOEs experiment is a very useful technique to determine the stereochemistry and structure of the molecule. For example, in dimethylformamide, the two methyl groups are nonequivalent, showing two signals at 31.1 and 36.2 ppm, because free rotation is restricted about the C–N bond due to resonance interaction between the lone pair on nitrogen and the π -bond of the carbonyl group.



Irradiation of the aldehyde hydrogen leads to a larger NOE for the carbon of the *syn*-methyl group (36.2 ppm) than for that of the *anti*-methyl group (31.1 ppm), allowing the peaks to be assigned. The *syn* methyl group is closer to the aldehyde hydrogen.

3. DEPT (Distortionless Enhancement by Polarization Transfer)

This technique used to determining the number of protons directly attached to the individual ¹³C nucleus i.e. we can interpret signals for CH₃, CH₂, CH and C. In the DEPT technique, the sample is irradiated with a complex sequence of pulses (in both the ¹³C and ¹H channels). Consequently, the carbon atoms attached with different number of hydrogen show different phases. Each type of carbon will behave slightly differently, depending on the duration of the complex pulses. These differences can be detected, and spectra produced in each experiment can be plotted.

One common method of presenting the results of a DEPT experiment is to plot four different **subspectra**. Each subspectrum provides different information and using this information, we can identify signals for all carbon atoms of the molecule. For example, DEPT plots for isopentyl acetate is given below:





(1) Bottom spectrum consists of signals for all carbon atoms i.e. this is ${}^{13}C{}^{1}H$ NMR spectrum.

(2) Next to bottom consists of signals for all carbon atoms attached to the hydrogens i.e. CH₃, CH₂, and CH (DEPT 45).

(3) The 3rd spectrum shows signals for only CH carbons (DEPT 90).

(4) In the last spectrum, CH and CH_3 carbons give +ve peak while CH_2 carbons give –ve peak (DEPT 135).

Through the mathematical manipulation of the results of each of the different DEPT pulse sequences, it is also possible to present the results as a series of subspectra in which only the CH carbons appear in one trace, only the CH_2 carbons appear in the second trace, and only the CH_3 carbons appear in the third trace etc. The DEPT plot for a palladium complex $[Pd(PhCHCHCH_2)(TMEDA)]^+$ is presented below:



(A) ${}^{13}C{}^{1}H$ NMR spectrum, (B) signals for CH₃ groups (C) signals for CH₂ groups (D) signals for CH groups and (E) quaternary carbon atoms only. Spectra (B), (C), (D) and (E) were obtained using variants of the DEPT pulse sequence.

4. DYNAMIC PROCESSES AND NMR SPECTROSCOPY

The timescale for NMR spectroscopy is longer than for most other spectroscopic methods (UV and FTIR) because relaxation times are of the order of milliseconds to seconds. This makes NMR spectroscopy a useful technique to study various types of intra- and intermolecular dynamic processes.

Intramolecular Processes (Fluxional process):

(i) Migration of ligand



(iii) Change in conformation



(ii) Rotation about bond



(iv) Spinning of ring



Intermolecular Processes (exchange processes): exchange of coordinated and uncoordinated ligands.



If there are two NMR active nuclei present in two different chemical environments, they give two separate signals with chemical shift difference of Δv Hz. However, if a process interchanges their environments with a rate (k) much faster than the Δv /sec, two nuclei observed as a single peak at an intermediate frequency. This is related to Heisenberg's Uncertainty Principle and also the origin of line broadening by dynamic phenomena. When rate of exchange (k) is comparable to the Δv , then a broad peak is observed. At coalescence (two signals merge together to give an intermediate signal), the rate of exchange is given by

$$\mathbf{k} = \frac{\pi \cdot \Delta v}{\sqrt{2}}$$

The millisecond timescale of NMR spectroscopy makes it particularly useful for monitoring dynamic processes with rates of the order of Hz to kHz, which are virtually impossible to study by any other method.

Effect of Temperature

Case 1: Cyclohexane interconversion: The ¹H NMR spectrum of a deuterated cyclohexane molecule $(C_6D_{11}H)$ as a function of temperature is shown in following figure.



The variable temperature ¹H NMR spectra of C₆D₁₁H

For this molecule two isomers are possible where the hydrogen is in either the axial or equatorial position of the cyclohexane ring. At room temperature, the two forms are rapidly interconverting and a sharp singlet is observed (a).



As the temperature is lowered, the peak begins to broaden (b). This range, down to the temperature at which the two separate peaks are just beginning to be resolved, is referred to as the *near fast exchange region*. Further lowering of temperature resulted the appearing of two peaks and their chemical shifts change as a function of temperature until curve (e) is obtained. This range is referred to as the *intermediate exchange region*. As the temperature is lowered further, the chemical shifts of the peaks no longer change, but the resonances sharpen throughout the so-called *slow exchange region*. Finally, at -79 °C and lower, there are no kinetic contributions to the shape of the spectrum, and this is referred to as the *stopped exchange region*.

Case 2: Cis-Trans Isomerization in [(C5H5)2Fe2(CO)4]

The ¹H NMR spectrum of complex $[(C_5H_5)_2Fe_2(CO)_4]$ shows two signals at lower temperature and only one signal at higher temperature. This complex exists as *cis* and *trans* isomers, which interconvert rapidly in the solution at higher temperature and therefore, NMR cannot differentiate *cis* and *trans* isomers and single peak is observed. However, at lower temperature, the interconversion is slow and we observe two peaks corresponding to *cis* and *trans* isomers.



Case 3: Stereochemical non-rigidity in trigonal bipyramidal (TBP) molecules (Berry Pseudorotation)

PF₅: The structure of PF₅ is trigonal bipyramidal with two axial 'F' and three equatorial 'F'. However, F atoms are indistinguishable by ¹⁹F NMR and a doublet (J_{PF}) is observed in ¹⁹F NMR spectrum of this compound. This indicates exchange of F_a and F_e is faster (Berry pseudorotation) than NMR time

scale and hence cannot distinguish axial and equatorial fluorine resulting a doublet with coupling with 'P' nucleus.



However, for a rigid trigonal bipyramidal structure (rate of pseudorotation is very slow) we expect a more complex pattern in ¹⁹F NMR of PF₅ (F_a as 'dq' and F_e as 'dt') as the F_a atoms belong to one chemically equivalent set and the F_e atoms belong to another chemically equivalent set.



PCl₂F₃: The rate of exchange of axial and equatorial groups can be slow down using bulky substituents and also lowering the temperature. PCl₂F₃ has TBP geometry with two 'F' atoms in axial positions and equatorial positions are occupied by two 'Cl' and one 'F' atoms. At temperatures of – 22 °C and above, all the fluorine atoms are equivalent and only a doublet ($J_{PF} = 1048$ Hz) is seen in the ¹⁹F NMR spectrum. However, if temperature is lowered to –143 °C, the exchange is stopped and two sets of peaks are appeared (i) at $\delta = +67.4$ ppm for two F_a as 'dd' ($J_{PF} = 1048$ Hz, $J_{FF} = 124$ Hz) and (ii) at $\delta = -41.5$ ppm for one F_e as 'dt' ($J_{PF} = 1048$ Hz, $J_{FF} = 124$ Hz).



ClF3 : Berry pseudorotation is stopped below -60 °C and ¹⁹F NMR spectrum shows one doublet for two axial F atoms and one triplet for one equatorial F atom.



SF4 : In this case, Berry pseudorotation is stopped below -100 °C and ¹⁹F NMR spectrum shows two triplets (one for 2 axial F atoms and other for 2 equatorial F atoms).



Fe(CO)s: ¹³C NMR spectrum shows only one peak (singlet) due to very fast exchange of axial and equatorial CO ligands. (FT-IR study indicates two types of CO)



 $Co_2(CO)_8$: Many isomers of $Co_2(CO)_8$ exist in the solution. They interconvert through fluxional process which exchanges the bridging and terminal CO ligands. This exchange is faster than NMR time scale and therefore, ¹³C NMR spectrum shows only a singlet peak.



Fluxional Organometallic Compounds

The crystal structure of $[(C_5H_5)_4Ti]$ shows two monohapto (η^1) and two pentahapto (η^5) cyclopentadienyl (cp) rings as shown in following figure:





A singlet peak is observed in ¹H NMR spectrum of this complex at 62 °C indicating all four cp rings are equivalent due to dynamic process. Lowering of the temperature causes peak broadening and finally splits into two sharp singlets at -27 °C. At this point, the process of interconversion

of η^1 and η^5 is very slow hence both configurations are observed in the spectrum. However, even at – 27 °C, η^1 -cp ring shows dynamic behavior so that three types of ring protons appeared as a singlet (instead of three lines with relative intensities 1:2:2) due to rapid migration of the metal from one site to another within each ring. At temperature –80 °C, expected signals appear for three nonequivalent ring protons.

Allene-metal complex, $[Fe(CO)_4(Me_2C=C=CMe_2)]$ also shows fluxional behavior. This compound exhibits only a single proton NMR peak at +30 °C. However, ¹H NMR spectrum taken at -60 °C shows three sharp peaks with relative intensities 1:1:2, for methyl groups (1), (2), and (3) + (4), respectively. It has been proposed that iron presumably migrates over C=C=C group making all 12 protons equivalent at higher temperature.



5. NMR OF PARAMAGNETIC COMPOUNDS

Although, NMR signals of paramagnetic molecules are generally broad, some paramagnetic compounds are useful reagents in high-resolution NMR studies. Also, many times NMR studies of paramagnetic species could be profitable and the consequences of the paramagnetism may be helpful in structure determination of the compounds. The *breadth of the resonances* and a *large expansion of the normal chemical shift* scale (e.g. more than 200 ppm for protons) are two most important characteristics of NMR spectra of paramagnetic compounds. The signals from diamagnetic compounds could also show these effects in the presence of paramagnetic species, even in low concentrations. The line broadening of the spectra is caused by fast relaxation (short electronic spin-lattice relaxation times) and/or hyperfine electron-nuclear coupling. In general, the chemical shifts of nuclei close to the paramagnetic center are more affected than those of nuclei that are further away. For example, the ¹H NMR spectra of [M{dimethyldi(phenylethynyl)aluminates}] (M = La, Pr, Sm, Ho and Tm) are shown below:



¹H NMR spectra: '*' represents the regions between 5 and 8 ppm; 'solv' denotes the position of the solvent signal.

Since, La^{3+} complex is diamagnetic, hence serves as a reference. The paramagnetic Sm^{3+} compound (5 unpaired f electrons) has chemical shifts very similar to the La complex. The chemical shifts in Tm^{3+} complex (2 unpaired f electrons) are very different; the AlMe₂ protons are 16 ppm upfield shifted. The ortho protons of the phenyl groups are closest to the Tm atom and are 20 ppm downfield shifted, whereas more distant meta and para protons downfield shifted by only ~6 ppm. The spectrum of the Ho³⁺ complex (4 unpaired f electrons) shows that the order of signals of methyl and orthophenyl hydrogen atoms are reversed. Such effects are difficult to predict.

The observed paramagnetic shifts in the NMR spectra of paramagnetic compound can be used to derive two important information (i) there is a through-space dipolar interaction between the magnetic moments of the electron and the resonating nucleus, which gives a dipolar shift, also sometimes known as a pseudocontact shift (often small in magnitude) (ii) coupling between the electron and the nucleus (contact shift) resulting a doublet in the NMR spectrum under conditions of slow electronic spin-lattice relaxation, but with a coupling constant ~1 x 10⁶ Hz! With such a large coupling, the intensities of the two resonances are not equal, so their weighted mean position is not at midpoint. Under fast relaxation, the doublet collapses into a singlet far away from the expected position – the contact shift.

Contact shifts give a measure of unpaired spin density at the resonating nucleus. Therefore, these are useful in studying the spin distribution in radical species, or in ligands in organometallic compounds.

The unusual properties of paramagnetic compounds can be useful in a variety of ways. In particular, the relaxation and chemical-shift effects can be so large that even small concentrations of paramagnetic materials can have dramatic effects on the NMR spectra of diamagnetic compounds. One such application involves 'shift reagents' paramagnetic lanthanide complexes, which are capable of spreading out overlapping resonances. An application still of some importance is the utilization of traces of paramagnetic material to reduce the relaxation times of slowly-relaxing nuclei, and so facilitate their study by Fourier-Transform methods.

6. SHIFT REAGENTS

Shift reagents, most commonly lanthanide complexes, are useful tools in NMR spectroscopy. They are capable of spreading out overlapping resonances and thus simplify NMR spectrum. This lead to easy interpretation of NMR spectrum. Chiral shift reagents can form diastereomeric complexes with chiral substrate for the determination of enantiomeric purity.



¹H NMR spectra of n-pentanol (A) without lanthanide reagent (B) in presence of the lanthanide reagent Achiral Lanthanide Shift Reagents with Hard Lewis Bases

The effects of paramagnetic lanthanide complexes on the NMR spectral characteristics of organic compounds have been known for some time. The use of these lanthanide complexes have widespread applications due to the ease of handling (they are air stable, commercially available, etc.) and the predictable nature of their effects on chemical shifts. The shifting in chemical shifts of proton and carbon nuclei in the NMR spectrum by lanthanide shift reagents (LSRs) is thought to be due to the Lewis acid/Lewis base complexation of the hexacoordinate Lewis acidic lanthanide shift reagent with a basic site (usually oxygen or nitrogen) on the molecule being analyzed. This complexation is in fast exchange with the unbound substrate and can take one of the following two possible forms. The first

possibility is a contact interaction where there is direct delocalization and/or spin polarization of the unpaired electron via the molecular orbitals of the substrate. Anisotropic effects similar to those caused by use of an aromatic solvent is the other possible type of "complexation" interaction (termed dipolar or "pseudo-contact" interactions), since paramagnetic materials exert stronger secondary magnetic fields than non-paramagnetic materials. With either mechanism, the induced shift effect falls off rapidly with increasing distance between the proton or carbon being analyzed and the shift reagent. For lanthanide shift reagents, contact interactions are greatly diminished due to the shielding of the unpaired electron by the s and p electrons, and the induced chemical shifts arise predominantly from the dipolar mechanism. Compilations of the lanthanide induced shifts of functional groups in monofunctional compounds show the following orders of donor power: $NH_2 > OH > ketones \approx esters > ethers > hioethers > nitriles; and P=O > amide C=O > C=S > P=S.$

Several lanthanide shift reagents have been found to be the best to use in terms of minimization of line broadening and magnitude of induced shift. These are Eu(III), Yb(III), Pr(III) or Dy(III) β -diketonate complexes.



Both Eu(III) and Yb(III) complexes induce downfield shifts, while Pr(III) and Dy(III) complexes induce upfield shifts. The relative ordering according to the magnitude of shift effects is: Dy > Pr \approx Yb > Eu. Since Eu causes the least line broadening of all lanthanides, it is the most utilized even though it induces the smallest chemical shift differences of the lanthanides. The most common β diketonate ligands used to make LSRs are 2,2,6,6-tetramethyl-3,5-heptanedionato (thd) (also called dipivalomethanoto or dpm), 1,1,1,2,2,3,3-heptafluoro-7,7,-dimethyl-4,6-octanedionato (fod), 1,1,1,2,2,3,3,7,7,7-decafluoro-4,6-heptanedionato (dfhd), 4,4,4-trifluoro-1-(2-thienyl)-1,3butanedionato (tta), 1,1,1-trifluoro-2,4-pentanedionato (tfa). Although, dfhd is a good substitute when the t-butyl resonances from the fod ligand interfere with the spectrum.



Common β -diketonate ligands for lanthanide shift reagents.

There was a report that $Eu(thd)_3$ decomposed in the presence of phenols and carboxylic acids, however, $Eu(fod)_3$ complex was found to be inert under these conditions. The $Ln(\beta-dik)_3$ complexes are soluble in a wide variety of organic solvents. One must realize, however, that certain solvents (acetone and acetonitrile) can themselves coordinate to the LSR and will hence reduce the shifts in the spectrum of the substrate. Widely used solvents are CCl₄, CDCl₃, CH₂Cl₂, Cl₂CHCHCl₂, CS₂, benzene, toluene, pentane, and cyclohexane. The larger shifts are seen in the nonpolar solvents, and the smallest shifts are seen in benzene and chloroform.

The resonance for TMS is also not affected by the addition of a LSR and is generally used as the internal standard. When an LSR is being utilized in an NMR shift experiment, the best results are generally obtained with incremental addition of the LSR, thus producing a series of spectra with varying [LSR]/[S] ratios. Since the concentration of the compound being analyzed has an effect on the shift result, either the LSR is added as a solid to prevent dilution of the substrate (a few milligrams on the tip of a spatula works well), or a solution of the LSR with known concentration is added to the substrate in the NMR tube. The latter method is more wasteful in terms of the substrate, as the procedure requires the use of several aliquots of the substrate with different concentrations of the LSR in order to maintain a constant concentration of the substrate. It is, however, more accurate in the amount of LSR being added.

Achiral Lanthanide Shift Reagents with Soft Lewis Bases

Combinations of lanthanide shift reagents and silver salts have been found to be very efficient in spreading out the resonances of soft Lewis bases such as aromatics, alkenes, alkynes, phosphines, and halogenated compounds. The silver in these binuclear complexes binds to the substrates and acts as a bridge between the soft Lewis base and the paramagnetic lanthanide nucleus, which induces the shifts. At least two equilibria exist in order for these shifts to occur: (1) the substrate S first coordinates to the silver β -diketonate, Ag(β -dik) and (2) the substrate/silver β -diketonate complex associates with the lanthanide tris(β -diketonate) to form a tetrakis complex.

(1) $Ag(\beta-dik) + S = Ag(\beta-dik)$ (S)

(2) $Ln(\beta-dik)_3 + Ag(\beta-dik)$ (S) = $Ln(\beta-dik)_4 Ag$ (S)

In practice, only one set of resonances is seen in these NMR spectra due to the rapid exchange between free and coordinated forms of substrates.

Olefins coordinate to silver more strongly than the other soft Lewis bases, and hence have the greatest induced shifts. *Cis* and *trans* olefin isomers can also be distinguished via this method. Under low shift reagent/substrate concentrations, the *cis* isomer binds more strongly due to its more steric accessibility than the *trans* isomer, and its resonances are shifted more than the trans isomer. In aromatic compounds, the location of the silver binding site may also be predicted on the basis of sterics. For example, in toluene, the para proton is shifted the most, as the silver is preferentially bound to the ring at a position furthermost removed from the methyl group. In halogenated compounds, secondary bromides, iodides, and tertiary chlorides react with the binuclear reagents presumably to produce silver halide salts. Therefore, only primary chlorides, bromides, iodides, and secondary chlorides can be used. The shift is largest with the iodo- derivative, as it is a softer Lewis base than the other halogens.

Eu(III) complexes are not as effective in inducing shift differences in the soft Lewis bases as with the hard Lewis bases. Yb(III) complexes are able to cause relatively large downfield shifts with the soft Lewis bases, and are the lanthanide complexes of choice with olefins and aromatics.

Pr(III) complexes are the best for upfield shifts and, of the various lanthanide complexes, provide the largest shifts for the phosphines. Shift effects with halogenated compounds are small due to the poorer ability of the halogens to complex with the shift reagents, and Dy(III) complexes (powerful upfield shifter) are preferred in these cases. However, since Eu(III) complexes still have the least broadening effect on the resonances of all the lanthanides, Eu(III) is the preferred lanthanide in studies of protons close to the olefin.

The ligands on both the lanthanide and silver chelates affect the magnitude of the induced shifts. For the Yb(III)/Ag(I) binuclear complex, the best ligands appear to be the fod, although, as before, dfhd is a good substitute when the *t*-butyl resonances from the fod ligand interfere with the spectrum. The best combination for upfield shifts is $Pr(fod)_3$ with Ag(tta) or Ag(tfa)]. Since the shifts seen with soft Lewis bases are small relative to those with hard Lewis bases, the solvents that can be employed are more limited. The following solvent order is in decreasing magnitude of induced shifts: pentane > cyclohexane > CDCl₃ ≈ CCl₄.

Chiral Shift Reagent: This contains chiral ligand and forms diastereomeric compounds with chiral substrate which gives different chemical shifts.





3-heptafluoropropylhydroxymethylene-D-camphoroto (hfc)