CHAPTER 1

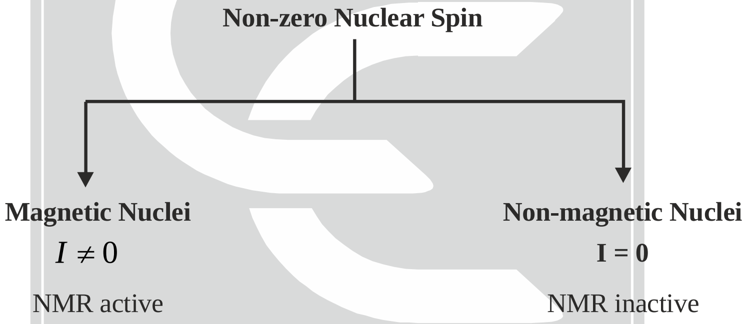
NUCLEAR MAGNETIC RESONANCE

Properties of nucleus to give NMR signal:

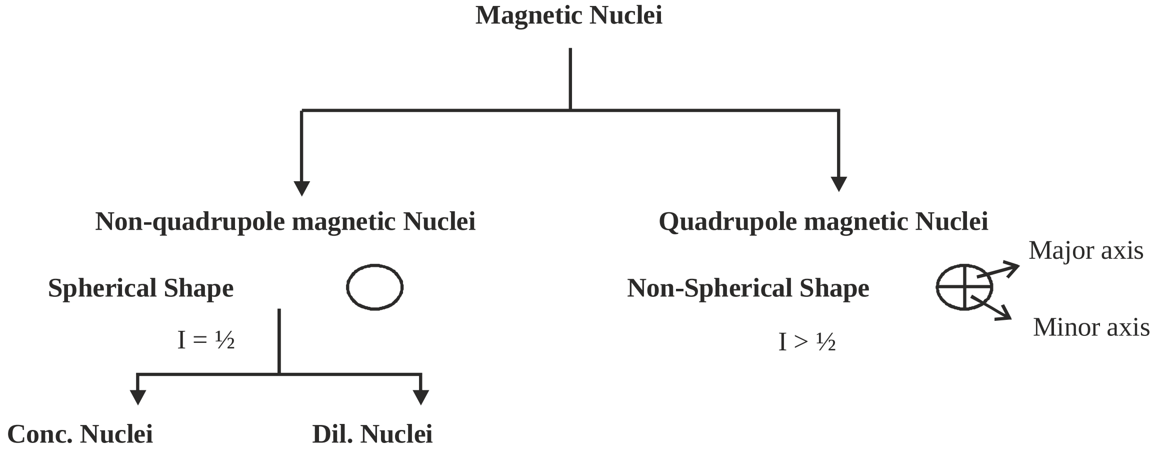
All the nucleus their isotopes present in periodic table are not NMR active. For a nucleus to be NMR active it should full fill/possess.

Non-zero Nuclear spin:

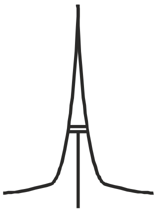
On the basis of spin number, nucleus can be divided into two types



- Mass number of non-magnetic nuclei will be completely divisible by 4.
  e.g. ^{16}O, ^{12}C, ^{32}S
- If not divisible by 4, then NMR active
- To obtain a good quality NMR signal from magnetic nuclei
- It should have good natural abundance and less quadrupole moment.
  On the basis of these two factors, magnetic nuclei can be classified as



- The NMR signal of non-quadrupole magnetic nuclei will be sharp
- In case of qudrupole nuclei due to less relaxation time, the NMR signals will be broad and sometimes it will not appear all.



$\Delta\bar{\nu}$ (band width)

If more, less $\Delta t\left(\text{relaxation time}\right)\times \underset{\text{frequency (signal width)}}{\Delta v} = \text{constant}$

Δt = more then $\Delta\bar{v}$ = less.

For quadrupolar nuclei Δt = very less. So, transition occurs so fast that signal becomes so broad.

If Δt = more i.e. relxation time is more then sharp signals.

I	**Atomic Mass**	**Atomic Number**	**Example (I)**
Half-integer	Odd	Odd or even	${}^{1}_{1}\text{H}\left(\frac{1}{2}\right),\ {}^{17}_{8}\text{O}\left(\frac{5}{2}\right),\ {}^{15}_{7}\text{N}\left(\frac{1}{2}\right)$
Integer	Even	Odd	${}^{2}_{1}\text{H}(1),\ {}^{14}_{7}\text{N}(1),\ {}^{10}_{5}\text{B}(3)$
Zero	Even	Even	${}^{12}_{6}\text{C}(0),\ {}^{16}_{8}\text{O}(0),\ {}^{36}_{16}\text{S}(0)$

Quadrupole enhances relaxation:

- The signal width in NMR is associate with the relaxation time of nucleus with exclusion principle.
- Presence of quadrupole moment creates fast relaxation of nucleus (less Δt) resulting broad .... of NMR signals.
- Non-quadrupole magnetic nuclei with high natural abundance is conc. nuclei.

$H^{1}\left(s=\frac{1}{2}\right)\rightarrow 99.8\%$

$P^{31}\left[s=\frac{1}{2}\right]\rightarrow 100\%$

$F^{19}\left[s=\frac{1}{2}\right]\rightarrow 100\%$

$Rh^{101}\left[\ell=\frac{1}{2}\right]\rightarrow 100\%$

- The nuclei having spin number more than $\frac{1}{2}$ i.e. $\left(I>\frac{1}{2}\right)$ are known as Quadrupolar nuclei.

  Recording of NMR spectrum for quadrupolar nuclei is always challenging.
  Since, the quadrupolar moment of nucleus causes broadening of NMR signal.

  The broadening of NMR signal is due to very less relaxation time $\left(\Delta t\right)$ for quadrupolar nuclei

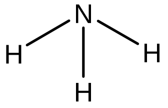
- The quadrupolar nuclei having less quadrupole moment $\Rightarrow$ less broadening.
  Quadrupole effect is only when there is gradient (concentration difference i.e. asymmetric electric field) in electric field.
  If symmetrical electric field $\Rightarrow$ no quadrupolar effect.

For example:

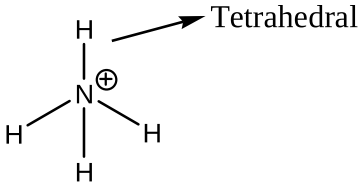
(i) The effect of quadrupolar broadening becomes negligible. If the nuclei is present in spherical electronic environment.

(ii) ^{15}N-NMR spectrum of NH_3 shows broad (Quartet) signal due to axial electronic environment.

But ^{15}N-NMR of NH_4^+ shows $\Rightarrow$ sharp signal.



Non-spherical symmetry
$\rightarrow$ broad signal
(Axial Symmetry)



N is in spherical symmetry $\rightarrow$ sharp signal

(iii) **^{1}H NMR spectrum of NH_3:**
Gives broad signal
But ^{1}H NMR of NH_4^+ gives sharp signal.

Dilute Nuclei:

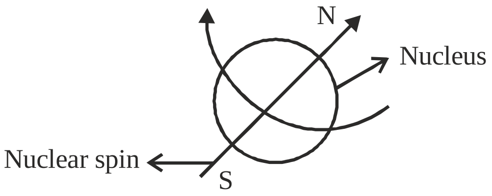
$$^{13}C\left[s=\frac{1}{2}\right]\rightarrow 1.1\% \quad \Rightarrow {}^{15}N\left[\ell=\frac{1}{2}\right]=0.37\%$$

$$^{199}Hg\left[s=\frac{1}{2}\right]=16\% \quad \Rightarrow {}^{29}Si\left[\ell=\frac{1}{2}\right]=5.1\%$$

Table - Properties of some nuclei with non-zero spin

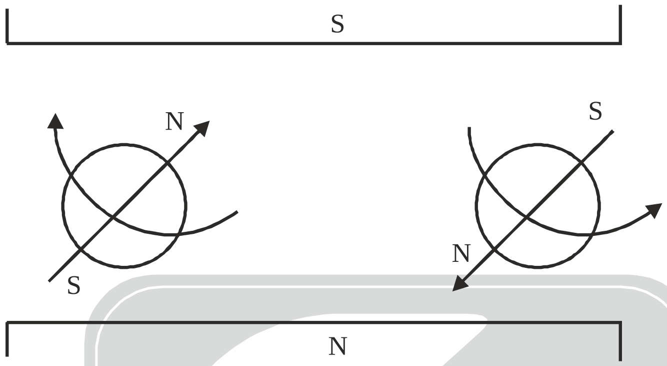
Nucleus	Spin	Resonance frequency (MHz) in field of 2.3487 T	g value
^{1}H	1/2	100.00	5.585
^{10}B	3	10.75	0.6002
^{11}B	3/2	32.08	1.792
^{13}C	1/2	25.14	1.404
^{14}N	1	7.22	0.4036
^{15}N	1/2	10.13	–0.5660
^{17}O	5/2	13.56	–0.7572
^{19}F	1/2	94.07	5.255
^{29}Si	1/2	19.87	–1.110
^{31}P	1/2	40.48	2.261
^{35}Cl	3/2	9.80	0.5472
^{37}Cl	3/2	8.16	0.4555
^{107}Ag	1/2	4.05	–0.2260
^{119}Sn	1/2	37.27	–2.082
^{127}I	5/2	20.00	1.118
^{199}Hg	1/2	17.83	0.996

NMR Phenomenon:

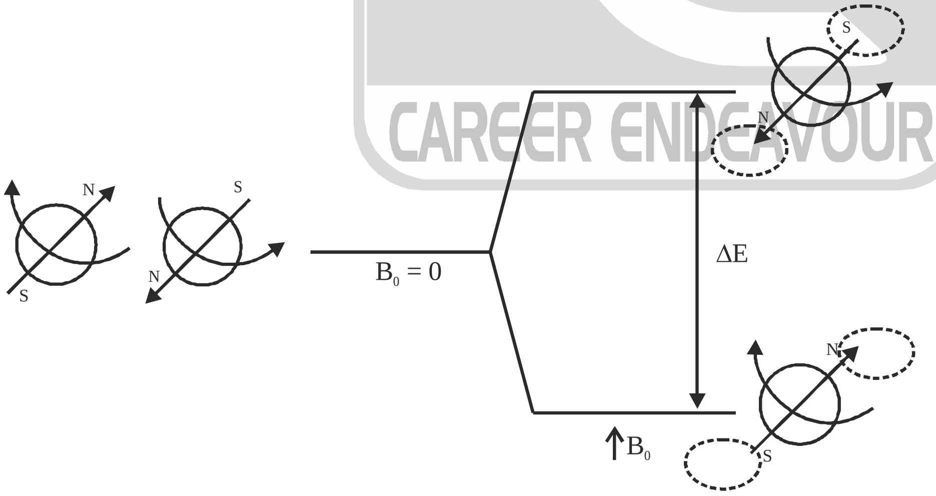


$$+\frac{1}{2}(\text{clockwise})$$
$$-\frac{1}{2}(\text{anti-clockwise})$$

Before magnetic field → energy same
After magnetic field → energy difference.



- In the absence of external magnetic field the nuclear spin energy level remain degenerate. As we apply the external magnetic field the degeneracy of spin energy level get break. The nucleus which are aligned with external magnetic field will remain in lower energy level and the nucleus apposing the ext. magnetic field will be in higher spin energy level.
- The distribution of nucleus into lower and higher energy level will be according to Botlzmann equation.



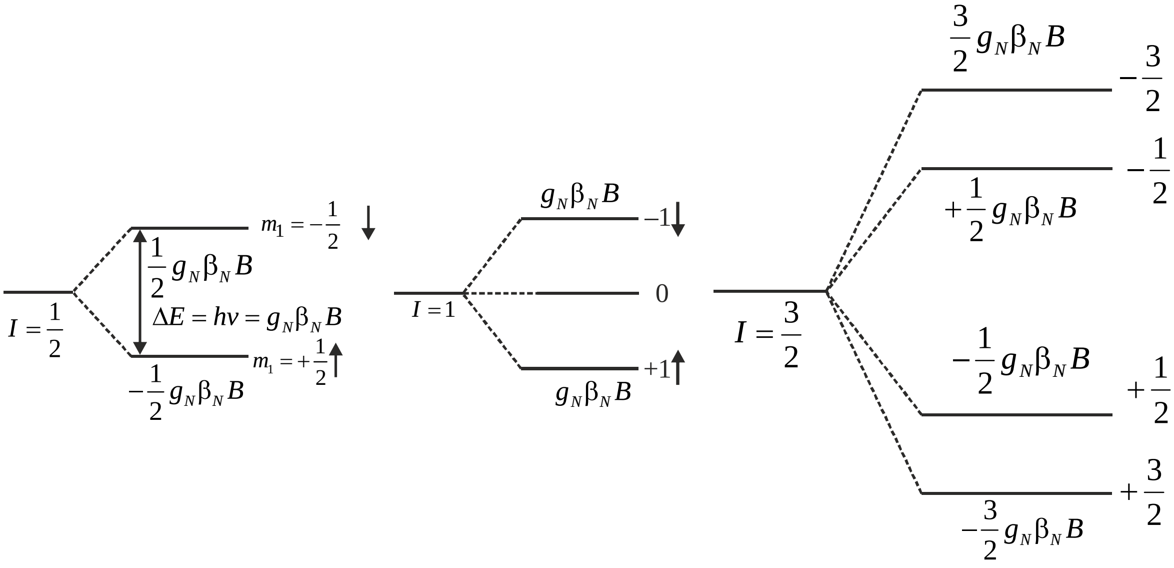


Figure : Splitting of nuclear spin energy levels in a magnetic field of strength B

- The separation of energy levels ΔE will be directly proportional to the applied magnetic field. The population difference [number of nucleus in ground state and number of nucleus in excited state] between the energy levels will be directly proportional to the applied magnetic field strength.

  The NMR signal strength will be directly proportional to the population difference.

  Apart from spin motion, the nucleus starts precessional motion due to external magnetic field, which is also known as gyroscopic motion.

  The frequency of gyroscopic motion will be known as pressional frequency.

  $$\boxed{PF \propto \gamma \cdot B_0}$$

  Where, γ = Gyroscopic ratio for nucleus

  $$\gamma = \frac{P.F.}{B_0} = \frac{MHz}{Tesla}, \quad \gamma = MHz/Tesla$$

If B_0 = 1 Tesla then γ = P.F.

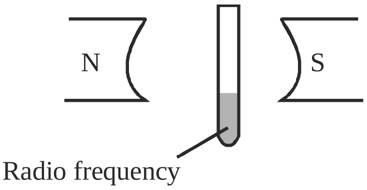
Gyromagnetic ratio will be precessional frequency of a particular nucleus at 1 Tesla magnetic field.

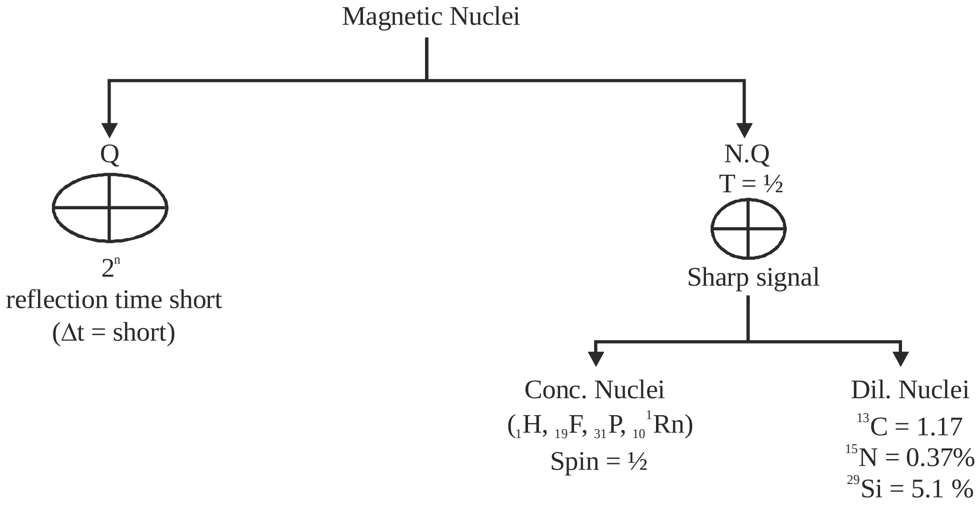
$^{1}H = 42.576 \quad MHz/T$

$^{13}C = 10.705 \quad MHz/T$

$^{31}P = 17.236 \; MHz/T$

$^{19}F = 40.053 \; MHz/T$





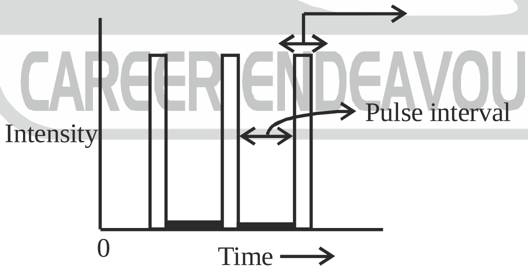
Where, Q = Quadrupolar, QN = Non-quadrupolar

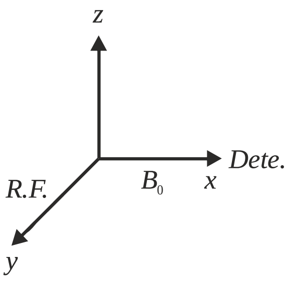
- When we external magnetic field to the sample the degeneracy spin energy level for break resulting the population difference according to Boltzmann equation.
- The nucleus starts precessional motion in the external magnetic moment and spin motion remain unaffected.

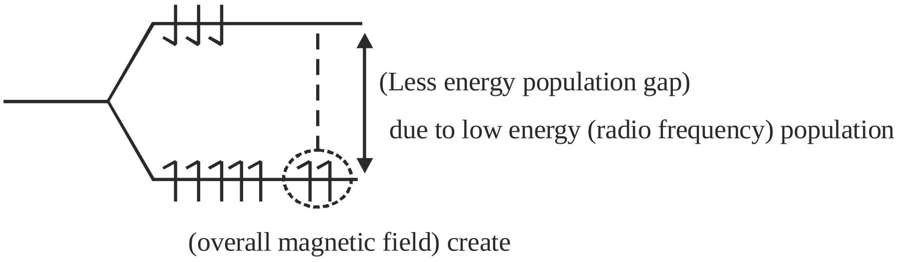
$$\left[P.F. = \gamma B_0\right]$$

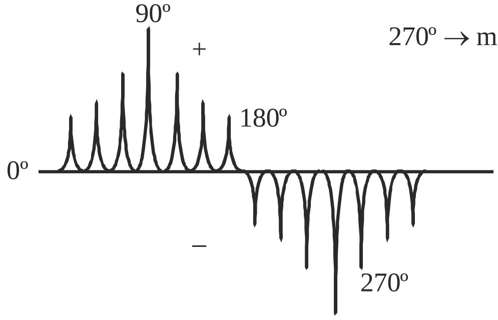
the precessional frequency will be equal to γB_0

- For generating NMR signals we needs to apply radio frequency pulse perpendicular to direction of external magnetic field.
- When PF will become equal to the applied radio frequency resonance will occur, the nuclear transition from ground state spin energy level to excited state spin energy level will result NMR signal.









- In NMR the energy gap between spin energy level is lowest compared to other spectroscopy due to least energy gap the (appr. 8 ppm/tesler)
- Population difference is also very small but it is much sufficient to produce NMR signal.
- Due to least energy gap the spin energy levels are very sensitive for saturation so we always apply the radio-frequency in the form of pulse.
- During pulse time spin transition will occur resulting the NMR signal and during pulse interval relaxation of nuclear spin will happence to recreate the population difference.
- A good quality NMR signal can be obtain as average signal of 15-50 pulses for H-NMR

  P.F. = γB_0

SOLVED PROBLEMS

1. Calculate the PF of H (proton) at 5T magnetic field

   1 T = 42.57 MHz

Soln. PF = γB_0

PF = 5×42.57 MHz = 212 MHz

2. Calculate the value of required magnetic field to resonate ^{19}F nucleus with 500 MHz radio frequency

Soln. PF = 500 MHz (Resonat energy)

$$\beta_0 = \frac{P.F.}{\gamma} = \frac{500}{40.05} = 12.5\,T$$

3. The P.F. of a proton on a NMR specrophotometer is 300 MHz. Calculate the PF of C-nucleus on the same instrument.

Soln. $P.F_{(H)} = \gamma B_0$

$P.F. = 300\ MHz$

$\gamma = 42.57$

$$\beta_0 = \frac{P.F.}{\gamma} = \frac{300}{42.57} = 7.02\,T$$

$\gamma = 10.705$ [for C]

$\beta_0 = 7.02\,T$

$P.F. = \gamma\beta_0 = 10.70 \times 7.02$

$PF_{BC} = 75.4\ MHz$

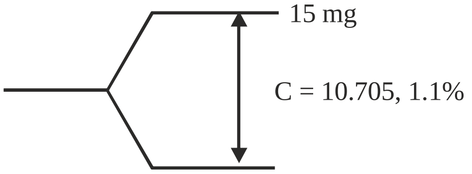
- In NMR the sensivity of nucleus can be reflected as result of sample requirement and NMR recording time.
- For high sensitive nucleus the sample requirement and NMR recording time will be higher
- The two major factor decide the sensitivity of nucleus

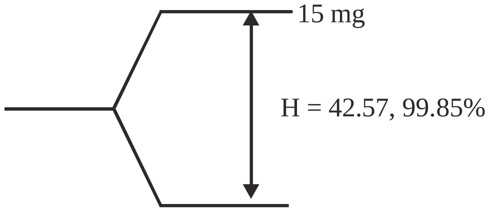
  (i) γ -Gyromagnetic

  (ii) N.A. (natural abundance)

  The nucleus having higher gyromag. ratio and higher N.A. are more sensitive.

  If γ is higher then separation of energy level for Tesla mag. field will be high.





resulting higher population difference, high number of possible transition and intense NMR signal.

- Higher natural abundance of nuclei will provide high conc. of NMR active nuclei in the sample to produce high instance signal.

e.g.	γ	$N.A.$	400 MHz	Relative sensitivity
	$^{13}C = 10.705$	1.1%	30 minutes/spectrum	1.7×10^{-4}
	$(\max.\gamma\ \text{ratio})\ ^{1}H = 42.57$	99.85%	30 minutes/spectrum	1.0

- The most sensitive NMR nuclei is proton [H] because it has maximum γ and almost 100% natural abundance.
- As a standard way we always report the sensitivity of NMR active nuclei with respect to proton and which is known as relative sensitivity.

Nomenclature of NMR instrument:

Nomenclature of NMR instrument is on proton.

TMS = Tetramethyl Silane Proton = 400 MHz

The nomenclature of intrument as per standard system can be given according to precessional frequency of TMS protons on that instrument.

400 MHz instrument means TMS protons resonate at 400 MHz precessional frequency on this instrument.

Problem: The operating frequency of NMR instrument is 500 MHz. Calculate the precessional frequency of ^{13}C, ^{31}P, ^{19}F on this instrument.

Soln. Operating frequency = 500 MHz for proton.

PF = γB_0

$$B_0 = \frac{PF}{\gamma} = \frac{500}{42.576} = 11.7 \text{ Tesla}$$

$$^{13}C \Rightarrow PF_{^{13}C} = 11.7 \times 10.705 = 125 \text{ MHz}$$

PF for ^{31}P = 11.7 ×17.235 = 201 MHz

PF for ^{19}F = 11.7 × 40.053 = 468 MHz

Now, maximum 900 MHz NMR instrument is available

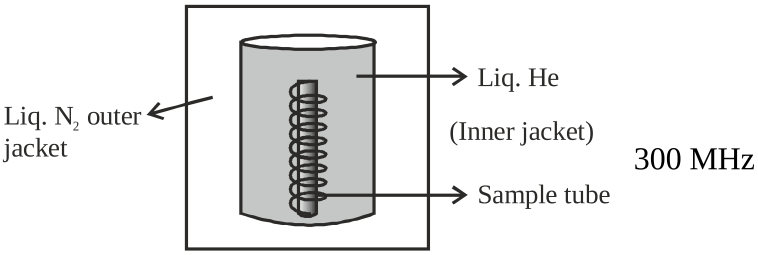
Therefore, magnetic field is fixed. So, we cannot make instrument upto 1800 MHz.

Why magnetic field $\rightarrow$ fixed

Therefore, maintaince is very high i.e. we have to pay for it.

Classical Magnet (Superconductivity): Large size magnet

After this discovery we can generate high magnetic field.



Superconductivity is not equal to zero. So, we have to maintain the heat treatment.

Problem: It is possible to create 900 MHz operating frequency instrument for proton but it is impossible to generate 900 MHz operating frequency for ^{13}C. Why?

Soln. 900 MHz instrument PF = γB

$$B = \frac{900 \text{ MHz}}{42.51} = 21 \text{ Tesla}$$

For ^{13}C $\rightarrow$ generate magnetic field = ?

$$\therefore \quad B = \frac{900 \text{ MHz}}{10.705} = 84 \text{ Tesla magnetic field}$$

(But limit is only 25 Tesla)

To resonate a proton at 900 MHz, we need 21 Tesla magnetic field which is the maximum limit of magnetic field present available and to resonate ^{13}C at 900 MHz, we need 84T magnetic field is practically impossible to create.

Sensitivity of nucleus for NMR :

The nucleus C give large signal peak i.e. more sensitive.

The sensitivity of nucleus means intensity of signal with respect to applied magnetic field.

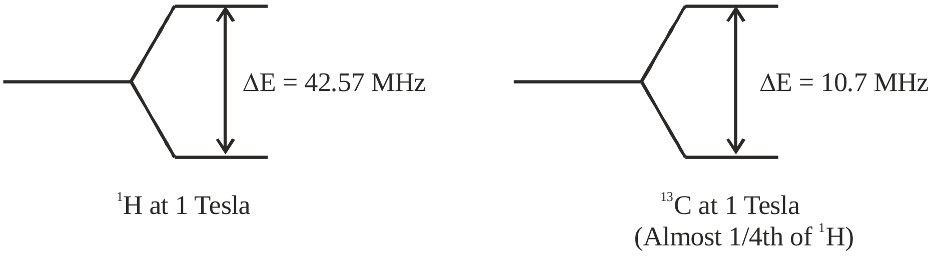
High sensitive nucleus gives intense signal with less amount of magnetic field. Proton is maximum sensitive i.e. lucky for scieintist.

The factors affecting sensitivity:

(1) Gyromagnetic ratio (2) Natural abundance

(1) Gyromagnetic ratio:

The nucleus having higher gyromagnetic ratio (r)



High γ ratio, sensitivity more.

Since, energy gap more. Population gap = more, number of transitions = more.

More intense signal.

Have higher separation between spin energy have resulting the higher population difference.

As per Boltzmann equation:

$$\boxed{\text{Signal intensity } \propto \text{ population difference}}$$

i.e. $\boxed{\text{Sensitivity} \propto \text{Gyromagnetic ratio}(\gamma)}$

(2) Natural Abundance:

The nuclear having higher natural abundance will be more sensitive.

For e.g. ^{1}H natural aboundance = 99.987

	Natural Abundance	**γ**	**Relative Sensitivity**
^{1}H	99.98%	42.576	1
^{13}C	1.1%	10.705	1.7×10^{-4}

^{13}C nucleus is almost 400 times less sensitive than proton ^{1}H nucleus.

Proton is the maximum sensitive nucleus. Since, it has maximum gyromag. ratio (r) and almost 100% natural abundance thats why the name of NMR instrument will be according to the operating frequency of proton (^{1}H).

Problem: A magnetic nuclei resonates with 300 MHz precessional frequency at an NMR instrument of operating frequency 500 MHz. Calculate the Gyromagnetic ratio for the nucleus.

Soln. NMR instrument frequency P.F. = 500 MHz

^{1}H, $\gamma = 42.576$ MHz

$$\text{P.F.} = \gamma\,B \qquad \Rightarrow B = \frac{500\text{ MHz}}{42.576\text{ MHz}} = 11.743$$

Resonating frequency = 300 MHz

$$B = 11.743 \qquad \Rightarrow \gamma = \frac{300\text{ MHz}}{11.743} = 25.54\text{ MHz}$$

Problem: Preessional frequency of Deuterium on NMR instrument is 50 MHz. Calculate the preessional frequency for ^{31}P at same instrument.

$$\boxed{\begin{aligned}\gamma_D &= 6.536\\ \gamma_P &= 17.235\end{aligned}}$$

Soln. P.F. for Deuterium = 50 MHz

$$\gamma_D = 6.536\text{ MHz} \quad \Rightarrow B = \frac{50\text{ MHz}}{6.536\text{ MHz}} = 7.64$$

$$\gamma_P = 17.235,\ B = 7.64$$

$$\text{P.F.} = 17.235\times7.64 = 131.64\ \text{ MHz}$$

Problem: Calculate the frequency of nuclear spin energy levels for ^{14}N nucleus in a magnetic field of 15.4 Tesla.

Soln. B = 15.4 Tesla

$$\gamma = 1.9331\times10^7\ \text{rad sec}^{-1}\,\text{T}^{-1}$$

$$\text{P.F.} = \gamma B = 15.4\times1.9331\times10^7 = 29.769\times10^7 = 297.69\times10^6$$

100 MHz instrument.

What happens when sensitivity increased

Since, on increase instrument sensitivity the amount decreases.

For e.g.	100 MHz	600 MHz
	Less sensitive	More sensitive

γ and natural abundance = constant for ^{13}C.

		100 MHz	600 MHz
^{13}C		45 min	10–15 min
Spectra		50 mg sample	20–25 mg

If magnetic field = increases → population difference increases → sensitivity increases.

Therefore, on increasing sensitivity on increases

Magnetic field → we get spectra is less time.

i.e. sample quantity less and required time for spectra decreases

600 MHz instrument is important for dilute nuclei. Its cost is so much high as compare to 100 MHz.

The sensitivity of dilute nucleus can be enhanced by increasing the magnetic field. Increases in sensitivity means requirement of less amount of sample and less NMR recording time.

For e.g. At 100 MHz instrument ^{13}C = one ^{13}C

NMR takes 45 minutes and 600 MHz takes 10–15 minutes.

For working on cancentrated nuclei → 300 MHz instrument is sufficient but for dilute nuclei = 600 MHz.

SOLVED PROBLEMS

1. The g_N value for F^{19} nucleus is 5.256. Calculate the resonance frequency when it is placed in a magnetic field of strength 1.0 T (tesla) and β_N is 5.0504×10^{-27} JT^{-1}. Also calculate relative population in two spin state at 300K.

Soln. The resonance condition from (9); $hv = g_N \beta_N B$, hence,

$$v = \frac{g_N \beta_N B}{h} = \frac{5.256 \times 5.0504 \times 10^{-27}\, JT^{-1} \times 1.0T}{6.626 \times 10^{-34}\, Js} \qquad \left(\frac{g_N \beta_N B}{h} = \text{Gyromagnetic ratio}\right)$$

$$= 4.006 \times 10^{7}\, s^{-1} = 40 MHz$$

The relative population in $M_I = -\frac{1}{2}$ and $M_I = \frac{1}{2}$ spin states from (10)

$$\frac{n_{-1/2}}{n_{1/2}} = e^{-g_N \beta_N B / k_B T} = \exp\left(-\frac{5.256 \times 5.0504 \times 10^{-27}\, JT^{-1} \times 1.0T}{1.38 \times 10^{-23}\, JK^{-1} \times 300K}\right)$$

2. A NMR spectrometer operating at a 60 MHz frequency gives proton spectra at a field of 1.4092T. At what field would the ^{11}B spectrum be observed at 60 MHz. (For ^{11}B, $I = \frac{3}{2}$ and g = 1.7920).

Soln. v = Operating frequency = 60 × 10^{6} hz

$$\text{and } = \frac{\Delta E}{h} = \frac{g_N \mu_N B}{h} = \frac{1.7920 \times 5.0504 \times 10^{-27}\, JT^{-1}}{6.626 \times 10^{-34}\, Js^{-1}} \times B$$

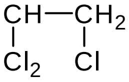
$$B = \frac{60 \times 10^{6} \times 6.626 \times 10^{-37}\, Js^{-1}}{1.7920 \times 5.0504 \times 10^{-27}\, JT^{-1}} = 43.93 \times 10^{-1} = 4.393T$$

3. Find the frequency at which a proton NMR spectrometer should be operating under a magnetic field 1.8. T ($g = 2.7245 \times 2$ and $\mu_N = 5.0504 \times 10^{-27}$ JT^{-1})

Soln. $\Delta E = g_N \mu_N B$ for transition for $M_I = \frac{1}{2} \to -\frac{1}{2}$ in proton

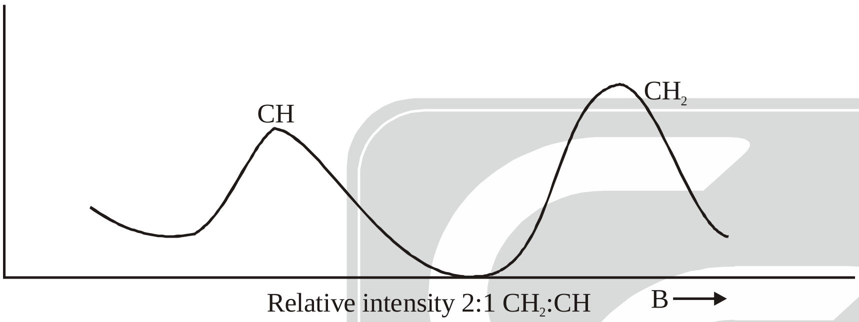
$$v = \frac{\Delta E}{h} = \frac{2 \times 2.7245 \times 5.0504 \times 10^{-27} JT^{-1} \times 1.8T}{6.626 \times 10^{34} Js^{-1}}$$

$$= 7.48 \times 10^7 Hz = 74.8 MHz$$

4. Sketch the NMR spectra of 

$$\underset{Cl_2}{CH}-\underset{Cl}{CH_2}$$

Soln.



Relative intensity 2:1 CH$_2$:CH

A spectroscopic technique that gives us information about the number and types of atoms in a molecules.

- Hydrogen using ^{1}H NMR spectroscopy
- Carbon using ^{13}C-NMR spectroscopy
- Phosphorus using ^{31}p-NMR spectroscopy
- Silicion using ^{29}Si-NMR spectroscopy
- ^{19}F NMR, ^{119}Sn NMR and ^{195}pt NMR.

5. The uncertainty in the NMR frequency of a compound in liquid state (relaxation time =1s) is 0.1 Hz. The uncertainty in the frequency (in Hz) of same compound in solid state (relaxation time$=10^{-4}$s) is

(a) 10^{-4} (b) 100 (c) 1000 (d) 10^{-3}

Soln. **(c)** From Heisenberg uncertaintity principle,

$$\Rightarrow \quad \Delta E . \Delta t \geq \frac{h}{4\pi} \qquad \Rightarrow \quad h \, \Delta \upsilon . \Delta t \geq \frac{h}{4\pi} \qquad \Rightarrow \Delta \upsilon . \Delta t \geq \frac{1}{4\pi}$$

Or $\Delta \upsilon . \Delta t \geq$ constant ...(i)

(where t = life time or Relaxation time and $\Delta \upsilon$ = uncertainty in frequency

$\therefore$ $(0.1 \text{ Hz})(1 \text{sec}) \geq$ constant ...(ii)

And $(\Delta \upsilon \text{ Hz})(10^{-4}) \geq$ constant ...(iii)

From equation (ii) and (iii)

$$0.1 \times 1 = \Delta \upsilon \times 10^{-4} \qquad \therefore \qquad \Delta \upsilon = 10^3 = 1000$$

6. What magnetic field strength is required for proton magnetic resonance at 220 MHz, Given: Thefactor 'g' for proton is 5.585.

Soln. Since, $\Delta V = \mu_N \, gB$

We have, $$B = \frac{\Delta V}{\mu_N g} = \frac{\left(220\times10^{6}\ s^{-1}\right)\left(6.626\times10^{-34}\ J\ s\right)}{\left(5.047\times10^{-27}\ J\ T^{-1}\right)\left(5.585\right)} = 5.1715\ T$$

7. Calculate the precessional frequency of a proton in a field of 1.5 T.

Soln. The precessional frequency is given by $v = \dfrac{\mu_N\ gB}{h}$

Hence, $$v = \frac{\left(5.047\times10^{-27}\ J\ T^{-1}\right)\left(5.85\right)\left(1.5\ T\right)}{\left(6.626\times10^{-34}\ J\ s\right)} = 6.38\times10^{7}\ s^{-1}$$

8. Calculate the value of gyromagnetic ratio γ.

Soln. Since, $$\gamma = \frac{2\pi\ \mu_N\ g}{h}$$

We have, $$\gamma = \frac{2\left(3.14\right)\left(5.047\times10^{-27}\ J\ T^{-1}\right)\left(5.584\right)}{\left(6.626\times10^{-34}\ J\ s\right)}$$

9. Calculate the angular momentum and magnetic moment values for a proton. Given: g = 5.585

Soln. We have, $$L = \sqrt{I\left(I+1\right)}\left(\frac{h}{2\pi}\right)$$

And $$\mu_m = g\ \mu_N\sqrt{I\left(I+1\right)}$$

For proton, I = 1/2. Thus, we have

$$L = \sqrt{\frac{1}{2}\left(\frac{1}{2}+1\right)}.\left(\frac{h}{2\pi}\right) = 0.866\left(\frac{h}{2\pi}\right) = 0.866\left(\frac{6.626\times10^{-34}\ J\ s}{2\times3.14}\right) = 0.9137\times10^{-34}\ J\ s$$

And $$\mu_m = \left(5.585\right)\left(\mu_N\right)\sqrt{\frac{1}{2}\left(\frac{1}{2}+1\right)} = 4.837\ \mu_N$$

$$= 4.837\left(5.047\times10^{-27}\ J\ T^{-1}\right) = 2.441\times10^{-26}\ J\ T^{-1}$$

PROBLEMS

1. Given $\gamma\left({}^{1}\text{H}\right) \simeq 2.7\times10^{8}\ \text{T}^{-1}\text{s}^{-1}$. The resonance frequency of a proton in magnetic field of 12.6 T is close to $\left(\pi = 3.14\right)$ **[NET Dec. 2013]**

(a) 60 MHz (b) 110 MHz (c) 540 MHz (d) 780 MHz

2. The nuclear g-factors of ^{1}H and ^{14}N are 5.6 and 0.40 respectively. If the magnetic field in an NMR spectrometer is set such that the proton resonates at 700 MHz, the ^{14}N nucleus would resonate at **[NET June 2015]**

(a) 1750 MHz (b) 700 MHz (c) 125 MHz (d) 50 MHz

3. In comparision to the frequency of the EPR transition, the NMR transition frequency is **[GATE 2001]**

(a) much higher (b) much lower (c) almost same (d) none of these

4. For any NMR active nucleus, the magnitude of radiofrequency required for observing nuclear magnetic resonance phenomenon depends on

(a) Strength of the magnetic field.
(b) Choice of the nucleus
(c) Both on magnetic field strength and choice of the nucleus.
(d) The nuclear enegy levels.

5. The sensitivity of a 600 MHz NMR spectrometer is more than that of a 60 MHz spectrometer because

(a) Population of spin states is directly proportional to the applied magnetic field. **[GATE 2003]**
(b) Population of spin states is inversely proportional to the applied magnetic field
(c) According to the Boltzmann distribution law, the excess population in the lower spin state increases with increasing applied magnetic field.
(d) The spectral scan width is more for a 600 MHz spectrum compared to a 60 MHz spectrum.

6. In NMR spectroscopy, the product of the nuclear 'g' factor (g_N), the nuclear magneton $\left(\beta_N\right)$ and the magnetic field strength (B_0) gives the **[NET June 2013]**

(a) energy of transition from α to β state (b) chemical shift
(c) spin-spin coupling constant (d) magnetogyric ratio