The Nuclei of Many Elements Are Magnetic

A spinning nucleus, composed of positively charged protons and uncharged neutrons. Circulation of charge (as in an electromagnet) leads to a magnetic field, indicated by the magnetic moment $\mu$. 

<table>
<thead>
<tr>
<th>Isotope</th>
<th>% Natural Abundance</th>
<th>Gyromagnetic Ratio ($\gamma / 10^7$ rad·s⁻¹·T⁻¹)</th>
<th>NMR Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>99.985</td>
<td>26.75</td>
<td>100.0</td>
</tr>
<tr>
<td>$^{13}$C</td>
<td>1.108</td>
<td>6.73</td>
<td>25.1</td>
</tr>
<tr>
<td>$^{15}$N</td>
<td>0.37</td>
<td>-2.71</td>
<td>10.1</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>100</td>
<td>25.18</td>
<td>94.1</td>
</tr>
<tr>
<td>$^{31}$P</td>
<td>100</td>
<td>10.84</td>
<td>40.5</td>
</tr>
</tbody>
</table>

$^\gamma$ MHz at 2.34 Tesla

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<th>Magnetic properties of various spin- nuclei.</th>
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The gyromagnetic ratio $\gamma$, is the ratio of the precessional frequency to the magnetic field. The precessional frequency $\omega_0$ is given in radians per second, and the magnetic field $B_0$ is given in Tesla.

$$\gamma = \frac{\omega_0}{B_0}$$

Precession of the nuclear magnetic moment in a cone around the external magnetic field.

Nuclear Precession in a Magnetic Field

When *averaged over time*, the magnetic moment is parallel to the magnetic field in one spin-state (upper cone), and anti-parallel to the magnetic field in the other spin state (lower cone).

Nuclear Magnetic Resonance Spectroscopy depends on observing populations of nuclei

The nuclear magnetic moments of all the nuclei in a sample add together to give a *net magnetization*. A small excess of nuclei adopt the parallel spin-state, so the sample itself becomes magnetized. At equilibrium, the net magnetization $\Sigma \mu$ is aligned with the magnetic field $B_0$. 

Magnetic Nuclei Interact with Magnetic Fields

A spin _ nucleus, such as $^1$H, $^{13}$C, and $^{15}$N, can adopt two different states in a magnetic field. These are called the *parallel* and *antiparallel* spin states.

The magnetic energy of the nucleus depends on the magnetic field strength $B_0$. As the field strength increases, the difference between the energy of the two spin states increases.

Magnetic nuclei *precess* in a magnetic field. *Coherent* precession of the nuclei can be induced by a brief, magnetic, radio-frequency (RF) pulse.

RF-Pulse

Magnetic Field

Magnetic Field

The Nuclear Magnetic Resonance Spectroscopy: A brief, magnetic, radio-frequency (RF) pulse is applied at the *resonance frequency* of a nucleus, resulting in a slight *shift in the precessional motion*. The field $B_0$ is turned off, and the *transverse magnetization* $M_T$ is excited by a *90° RF pulse*. This causes the precessional motion to change from a circular path to an ellipse, creating a *membrane* of nuclear spins. The *180° pulse* then flips the spins back to their original direction, restoring the original *magnetization*.
Nuclear Magnetic Moment Orientations are Redistributed by a Radio-Frequency (RF) Pulse

The RF field interacts with the nuclei, leading to a change in spin state and a change of the phase of each affected nuclear spins. This leads to the “bunching up” of nuclear magnetic moments. The net magnetization then precesses around the z-axis at a characteristic frequency that depends on the magnetic field.

As the Magnetization Vector Rotates, It Induces a Time-Domain Current in the Detector Coil. This is Called a Free Induction Decay (FID)

Fourier Transformation is used to Convert the Time-Domain Signal (FID) to a Frequency Domain Signal (the Spectrum)

Electron Circulation Shields the Nucleus from the Applied Field, Resulting in an Effective Field $B_{\text{eff}}$ that is Smaller than $B_0$

The applied field induces a circulating motion of the electrons surrounding the nucleus. This circulation generates a magnetic field that points in the direction opposite to the applied field. The net result is that the electrons decrease the effective magnetic field at the nucleus, decreasing its Larmor frequency.

A RF Pulse Can Result in the Rotation of Magnetization into the “Transverse Plane”

The (observable) amount of magnetization that is rotated into the transverse plane depends on the initial amount of magnetization along the z-axis. Nuclear interactions often affect the amount of z-magnetization, so RF-pulses allow us to indirectly observe nuclear interactions.

Electronic Shielding Changes the Frequency of the Magnetic Resonance

Since different nuclei in a molecule are in different electronic environments, you can keep track of each nucleus by assigning its characteristic frequency.
Magnetic Nuclei Interact with Each Other

Two types of interaction
- Scalar – Through Bonds
- Dipolar – Through Space

Both Types of Interaction Can Provide Information about the Geometry of a Molecule

Scalar Coupling Leads to the Splitting of Resonances to Give Multiplets (doublets, triplets, etc.)

The Scalar Coupling Constant Provides Information Regarding the Geometry of the Molecule

The Anomeric Configuration of a Sugar (α vs. β) Can be Distinguished by 1H-NMR

Changing the orientation of the anomeric proton affects its frequency and its scalar coupling to H-2.

Dipolar Coupling Arises from the Direct (Through Space) Interaction of Nuclei

The magnitude of the dipolar coupling $D$ depends on the distance $r$ between the nuclei and the angle $\theta$ between the internuclear vector and the applied magnetic field. $A$ and $B$ represent two interacting nuclei.

In freely tumbling molecules in solution, $D$ averages to zero.
Dipolar Coupling Leads to Relaxation Back to the Equilibrium State

When molecules tumble, the dipolar coupling oscillates at the same frequency as the molecular rotation, leading to an oscillating magnetic field. This can induce spin-state transitions the same way an RF-pulse does. However, the oscillations due to dipolar coupling are random, and lead to a return to the equilibrium state, which is the most random possible state for the collection of nuclear spins.

NMR Can Provide Information about Carbohydrate-Protein Interactions

- Binding Site
- Chemical Shift Measurements
- Binding Constant
- Chemical Shift Titration
- Binding Orientation
- Residual Dipolar Couplings


Dipolar Coupling Can Provide Geometric and Dynamic Information

- NOE (Nuclear Overhauser Effect) distance between nuclei
- RDC (Residual Dipolar Coupling) average orientation
- Relaxation Time ($T_1$, $T_2$) dynamic rotational properties

NMR Chemical Shifts Change when a Carbohydrate Binds to a Protein


Carbohydrate-Protein Interactions

Fig. 2. Titrations. (A) Titration study of 0.18 mm WGA-B in $^1$H$_2$O with increasing amounts of chitotriose at 298 K and pH 5.6. The variations of the NH proton of E33 can be easily followed. Total chitotriose concentration is indicated on the left. (B) Titration plot for chitotriose binding to WGA-B: dependence on temperature. The binding constants (M$^{-1}$) obtained are shown.