Simple and Inexpensive Classroom Demonstrations of Nuclear Magnetic Resonance and Magnetic Resonance Imaging

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5 AUTHORS, INCLUDING:

Marla A Chesnik
Medical College of Wisconsin

Clark R Landis
University of Wisconsin–Madison

Tested Demonstrations

Simple and Inexpensive Classroom Demonstrations of Nuclear Magnetic Resonance and Magnetic Resonance Imaging

submitted by: Joel A. Olson, Karen J. Nordell, Marla A. Chesnik, Clark R. Landis, and Arthur B. Ellis*
Department of Chemistry, University of Wisconsin-Madison, Madison, WI 53706-1396;
*ellis@chem.wisc.edu

M. S. Rzchowski
Department of Physics, University of Wisconsin-Madison, Madison, WI 53706-1396

S. Michael Condren
Department of Chemistry, Christian Brothers University, Memphis, TN 38104

George C. Lisensky
Department of Chemistry, Beloit College, Beloit, WI 53511

checked by: James W. Long
Department of Chemistry, University of Oregon, Eugene, OR 97403-1253

Background

Since its introduction in the 1950s, nuclear magnetic resonance (NMR) has become a powerful tool for the structural determination of chemical species. As an example of the utility of NMR spectroscopy, the initially proposed soccer ball structure of buckminsterfullerene (C_{60}) was controversial until its single-resonance ^{13}C NMR spectrum was observed (*1*). From its original use to study small molecules, NMR has rapidly expanded so that now its applications include large biopolymers and living organisms. In particular, spatially resolved NMR, or magnetic resonance imaging (MRI), has become a standard tool for the diagnosis of disease and injury.

Discussion of NMR and MRI experimental techniques can be integrated into introductory chemistry courses as a means of identifying for students how molecular structural features (with NMR) and spatially resolved tissue structural features (with MRI) can be determined. In the case of molecular species, the symmetry of molecules provides an intuitive basis for students to predict some of the key features of NMR spectra (*2–4*).

One of the most challenging aspects of describing NMR and MRI experiments is conveying the notion of resonance. Spin-½ nuclei like ^1H and ^{13}C can be regarded as magnetic dipoles. In the presence of an applied magnetic field (*B*), the nuclei precess at a natural oscillation frequency called the Larmor frequency. The precessing dipoles will align with or be opposed to the field by a quantum mechanical effect, corresponding to being in lower or higher energy states, respectively. As shown in Figure 1, the separation of the two energy levels, ΔE, increases linearly with magnetic field strength.

If the nuclei are irradiated with electromagnetic radiation whose frequency, ν, matches the precessional frequency, transitions between the two energy levels can occur by a resonant effect. This fundamental relationship underlying the NMR experiment equates the precession frequency to the spectroscopically observed energy difference between the two states, $\Delta E = h\nu$ (Planck relationship). Through the Planck relationship, Figure 1 illustrates that the resonance frequency increases linearly with applied magnetic field strength. The energies involved in NMR correspond to the radio frequency (rf) portion of the electromagnetic spectrum. Detection of signals in NMR and MRI experiments requires an excess of nuclei in the lower energy state at thermal equilibrium, and this population difference also increases with magnetic field strength.[1]

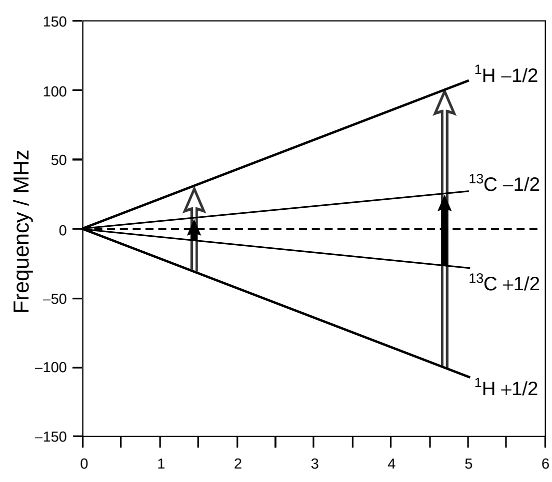

Figure 1. Field–frequency diagram, showing the energy levels of ^1H and ^{13}C nuclear spin states (−1/2 and +1/2) as a function of applied magnetic field strength, *B*. Note that the vertical axis is given in MHz, corresponding to the radio frequency portion of the electromagnetic spectrum. The transitions at 1.4092 tesla show the ^1H resonance frequency to be 60 MHz (outlined vertical arrow) and the ^{13}C resonance frequency to be 15.1 MHz (solid vertical arrow). The transitions at 4.6986 tesla correspond to 200 MHz ^1H (outlined vertical arrow) and 50.3 MHz ^{13}C (solid vertical arrow) resonances. The lower frequencies for the ^{13}C resonances reflect the smaller magnetogyric ratio of the nucleus.

This article describes a set of simple, inexpensive, classical demonstrations of NMR and MRI principles that illustrate the resonance condition associated with magnetic dipoles and the dependence of the resonance frequency on environment. The mechanical analogy underpinning the demonstrations is the use of common orienteering compasses to represent the dipoles of magnetic nuclei, in a static magnetic field provided by three collinear, strong permanent magnets; the static field is laterally homogeneous and decreases in strength with distance from the magnets. The compass needles are then excited by either a magnetic stir plate that provides a continuously oscillating magnetic field, or by a pulse from an electromagnet. This experiment is readily extended to show the effects of electronic shielding, spin–spin coupling, magnetogyric ratio, and free induction decay, topics that are routinely discussed in more advanced treatments of magnetic resonance phenomena. The fundamental concepts of the MRI experiment can be shown with the same apparatus. Sections below describe these mechanical analogies of resonance under various experimental conditions and their relationships to the NMR and MRI experiments.

Preparing and Conducting the NMR and MRI Demonstrations

The demonstrations described in this paper are designed for use with an overhead projector.[2] For all of the demonstrations, a trio of collinear permanent magnets is constructed to provide a magnetic field that is laterally uniform but whose strength decreases as the distance from the magnets increases. Two kinds of magnets were investigated for generating such a field: low-cost craft magnets and Nd–Fe–B rare-earth permanent magnets. (**Warning:** Any strong magnets should be kept away from sensitive electronic equipment and credit cards.) Commercially available compasses, the magnetic dipoles used in the demonstrations, frequently contain mineral oil as a means of damping the needle oscillations. The mineral oil is removed and the interior of the compass is cleaned to allow uninhibited and prolonged oscillation of the needle. As a means of providing energy input, either a magnetic stir plate or an electromagnet is required.

Supplies

Compasses[3]
Magnets: craft and Nd–Fe–B[4]
Magnetic stir plate[5]
Resistor: 10 W, 10 Ω[6]
9-V battery holder[7]
Mini momentary switch[8]
Wire[9]

Metal ring: bend a 1-in.-wide ribbon of metal into a circle with a diameter of several inches; 1-in.-wide 26 ga. galvanized paint lock (thin sheet steel) bent into a circle will work well. A steel soup or tuna can (galvanized or tin plated) with the top and bottom cut out works well also.

Permanent Magnet Configuration

The craft magnets generate a field that is slightly weaker and less uniform than the Nd–Fe–B magnets described below, but they are substantially cheaper and easier to assemble. The north and south faces of the craft magnets are the large faces shown in Figure 2a. For either kind of magnets (craft or Nd–Fe–B), care should be taken to align the north-poled faces in the same direction. Owing to the orientation of the three magnets in this array, the magnets will strongly repel each other and should be fixed in position. Since the craft magnets are already encased, they can be glued directly to a piece of Plexiglas or other nonmagnetic material (Fig. 2a).

Alternatively, three $\frac{5}{16} \times \frac{5}{16} \times 1\frac{1}{2}$ Nd–Fe–B rare-earth permanent magnets can be used.

> **Warning:** Nd–Fe–B magnets are magnetically very strong but mechanically brittle. They should be handled with care. Uncoated Nd–Fe–B magnets are susceptible to corrosion; they should be stored so as to minimize their exposure to air and moisture. Nd–Fe–B magnets should be kept away from sensitive electronic equipment and credit cards. Individuals with pacemakers should not handle these magnets. If the magnets are not secured properly, they can snap together, fracture, and spark, possibly injuring persons nearby.

The north and south ends of the rare-earth magnets are not the small ends of the bar, but rather the opposite long faces of the bar (Fig. 2b). To determine which two opposing long faces of the magnet are single-poled, place one of the drained compasses (see below) and one of the magnets several inches apart, with the long axis of the magnet vertical. If the compass needle points directly at the magnet, that face of the magnet is single-poled. For this array, these very strong magnets should be securely mounted to prevent their colliding, which might fracture them. For this reason, and for the purpose of reducing corrosion, we recommend encasing the magnets in clear Plexiglas, as shown in Figure 2b.

It is important that the compasses and metal shielding ring (see below) be kept away from the magnets so that these items do not become improperly magnetized. The permanent

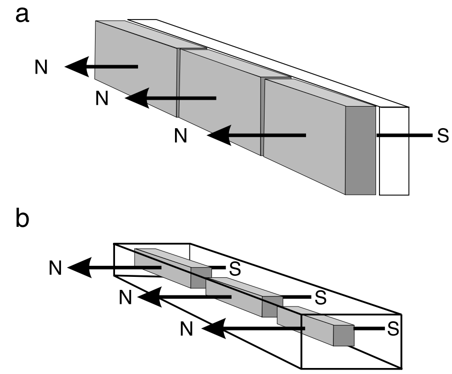

Figure 2. **Caution**: Please see the warning in the text regarding the handling of strong magnets. (a) A perspective view of the arrangement of the craft magnets for the demonstrations. The single-poled faces are the large faces of the craft magnets. Note that this is an unstable configuration for the magnets, and if they are not mounted securely, they will attract one another and change their configuration. (b) A perspective view of the arrangement of the Nd–Fe–B magnets for the demonstrations. The magnetic poles are not the ends, as is most common in bar magnets, but rather they are on opposite long faces of the magnets. Note that, as is the case for the craft magnets, this is an unstable configuration, and if the magnets are not mounted securely, they will attract one another and change their configuration.

magnet array, whether constructed with craft magnets or Nd–Fe–B magnets, should be at the same height as the compasses. If needed, a riser or spacer should be used to raise the level of the magnet array to the level of the compasses.

Compass Preparation

Small (1-in.), transparent, colorless plastic compasses work well on an overhead projector. In no case should a compass be used that is housed in a metallic case, as the case may become permanently magnetized. The mineral oil can be removed by carefully drilling a $\frac{1}{16}$-in. hole through the top and the bottom of the compass and allowing the oil to drain. The compass interior can be cleaned by rinsing with hot, soapy water. Use of an organic solvent may remove paint from the needle. Many compasses are mounted onto rectangular bases that are larger than the compass itself. Cutting off excess base that extends beyond the compass allows more compasses to be placed in the magnetic field. One compass should be left unaltered for use as a “standard” for checking magnetic field lines and the magnetization of modified compasses.

When a compass is moved too close to one of the strong permanent magnets, its needle may become improperly magnetized. For this reason the compasses and permanent magnets should be kept at least six inches apart except during the demonstrations. Compass magnetization can be checked by comparing the needle direction of a suspect compass with that of the “standard” compass needle known to be operating properly. If a compass needle is behaving improperly, it may be remagnetized by moving it close to a strong permanent magnet and then carefully withdrawing the compass in a direction perpendicular to the north or south face of the permanent magnet. For the demonstrations described here, it will be assumed that the compass needles possess their original magnetization. The demonstrations included in this paper involve one, two, three, or five compasses, but owing to variations in commercial compasses, it is advisable to purchase and drain several extra compasses so that a set of compasses that behave in a similar manner is available.

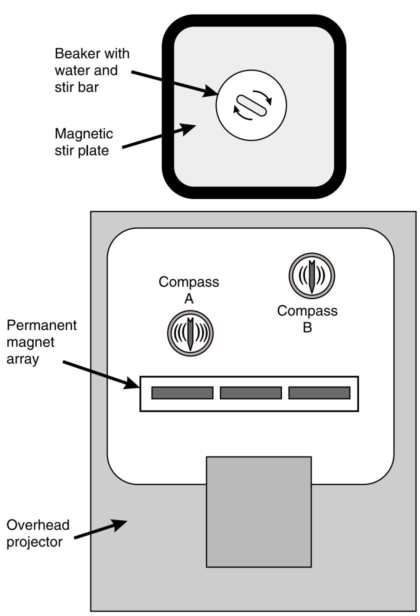

Figure 3. A top view of the setup for the demonstration of resonance using a magnetic stir plate. In order for the compass needles to be level, the compass needles, permanent magnet array, and rotating magnet in the magnetic stirrer should all be at the same height. Because compass A is closer to the permanent magnets and thus exposed to a stronger magnetic field, it will resonate at a higher frequency than compass B.

Resonance Using a Continuously Oscillating Magnetic Field

A magnetic stir plate with an adjustable stirring rate provides a continuously oscillating magnetic field. By using the magnetic stir plate to rotate a 1-in. stir bar placed in a beaker (150–250 mL) of water on top of the stir plate, the frequency at which the magnet rotates can be heard and amplified with a microphone in a large lecture hall. The positioning of the trio of permanent magnets, a pair of compasses, and the magnetic stir plate for this demonstration is shown in Figure 3.

Before conducting the demonstration, check that the stir plate, compass needles, and permanent magnets are at about the same height so that the compass needles are horizontal. Turn the magnetic stirrer on and adjust its frequency. Each compass needle will come into resonance at a different frequency, with the resonant condition characterized by oscillations with a large and constant amplitude. The compass closest to the permanent magnet array will resonate at the higher frequency. The resonant frequency can be approached from either direction. Observing resonance requires very careful adjustment of the stirring rate to not sweep through resonance without seeing it.[10] A particularly compelling feature of this demonstration is that the audience will be able to see that the resonance frequency of the compass needle matches the acoustic frequency of the rotating stir bar if its sound is audible.

To emphasize the dependence of a needle’s resonance on the presence of the magnetic field of the permanent magnets, remove the array of permanent magnets while one of the compasses is in resonance and observe the change in the needle’s behavior. To demonstrate the dependence of the resonance frequency on the strength of the magnetic field from the array of permanent magnets, move a compass that is in resonance slightly closer to or farther from the array of permanent magnets and observe the loss of resonance.

Preparation and Demonstrations Using a Pulsed Electromagnet

Compass needles in the presence of the static magnetic field are excited by a pulse from electromagnets. The pulse disturbs the needles’ equilibrium condition and the oscillation frequency of each needle is observed as the system returns to equilibrium. The oscillation frequency can be seen to depend on the compass’s position in the magnetic field. Variations of this demonstration can be used to illustrate the concepts of electronic shielding, spin–spin coupling, magnetogyric ratio, and free induction decay. In addition to the compasses and the array of permanent magnets described above, this demonstration involves the components described below.

Base Preparation and Assembly

A base for this demonstration is constructed from $\frac{1}{4}$-in. Plexiglas (or other clear acrylic sheet), cut to the dimensions given in Figure 4. Pieces B and C are recommended to protect the electromagnets and other electronic components, but are not required. To prepare piece A for the electromagnet coils, switch, and battery connections, drill the holes described in Figure 4. After the holes have been drilled in piece A, the four pieces marked B and C are fixed to the underside edges of A as shown, using glue or epoxy.

Coil Winding and Mounting

Insulated Cu wire (24 awg) was wound onto ferrous steel rods ($\frac{3}{8}$-in. diameter, 5.5 in. long). The winding can be done most easily on a lathe or reversible variable-speed drill, but the coils can also be wound by hand. Assembly will be simpler if one coil is wound clockwise and the other counterclockwise. Leave at least 12 in. of wire extending from each end of the coils to make connections. The wire can be either glued or taped in place on the ends of the rods to prevent unwinding. The coils can be mounted to the underside of piece A using plastic ($\frac{3}{8}$-in.) cable clamps and 6-32 nylon screws and nuts.

Making the Connections

If the coils have been wound in opposite directions, wire connections should be arranged and soldered as shown by the solid lines in Figure 5. If the two coils have been wound in the same direction, wire connections should be arranged and soldered as shown by the dotted lines in Figure 5. Special care should be taken to align the magnetic fields generated by each of the electromagnets so that they are parallel, with the north end of every electromagnet pointing in the same direction. Magnetic field alignment can be checked by positioning a compass near each electromagnet while current is flowing. The north end of the compass needle should point in the same direction regardless of position between the electromagnets. If the north ends of the electromagnets are not pointing in the same direction, one of the coils should be flipped without altering the connections. A momentary push button switch is preferred, but it must be a normally open momentary switch (i.e., in its open state until pushed).

> **Warning:** A normally closed switch (i.e., in its closed state until pushed) will allow current to flow continuously, which may result in extreme heating of the resistor and explosion of the battery.

A 10-Ω, 10-W resistor is connected in series with the two coils, switch, and battery. A battery mount may be used or the battery can be attached directly to piece A with double-stick foam tape. The region between the two electromagnets, defined by the dotted box in Figure 5, is the area in which the compasses may be placed for the demonstration. This region will be referred to as the “compass corral”.

Single-Compass Demonstration

A drawing of the relative placement of the compass, permanent magnet array, and electromagnets with their magnetic field lines is shown in Figure 6. Note that the north–south field lines of the bar magnets must be perpendicular to the north–south field lines of the electromagnets. It may aid understanding to show a transparency overlay indicating the field lines from both the permanent magnets and the electromagnets over piece A, as shown in Figure 6. When the switch is depressed, the compass needle is excited owing to the resulting field, which is perpendicular to the magnetic field of the permanent magnets. This pulse should cause the compass needle to oscillate at a specific frequency. Varying the distance between the compass and the permanent magnets visibly changes the frequency of oscillation.

This demonstration provides a clear analogy for the proportionality of the oscillation frequency and the magnetic field strength, as observed in NMR experiments. It is note-

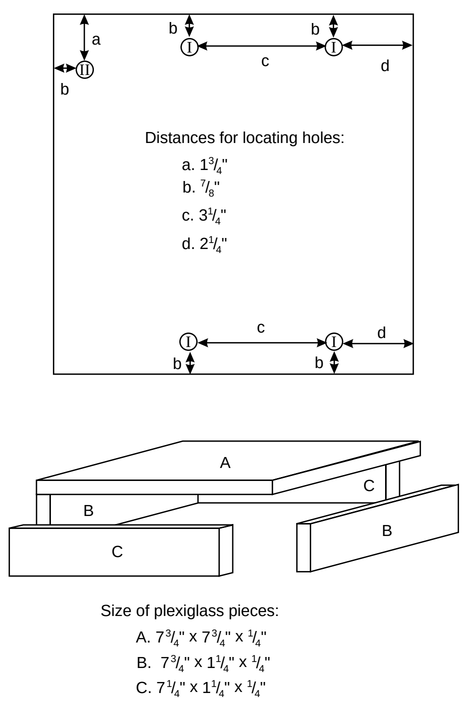

Figure 4. A schematic of the construction of the base used for the demonstration with electromagnets. Pieces A, B, and C are all cut from 1/4-in. thick Plexiglas or other clear plastic. Piece A (top) requires holes drilled at the indicated positions. The holes labeled (I) should have 9/64 in. clearance for 6-32 nylon flathead screws, which hold the clips for the electromagnet coils. Use a standard countersink tool to recess the screw heads. Hole (II) is a 5/16-in. hole for the momentary switch.

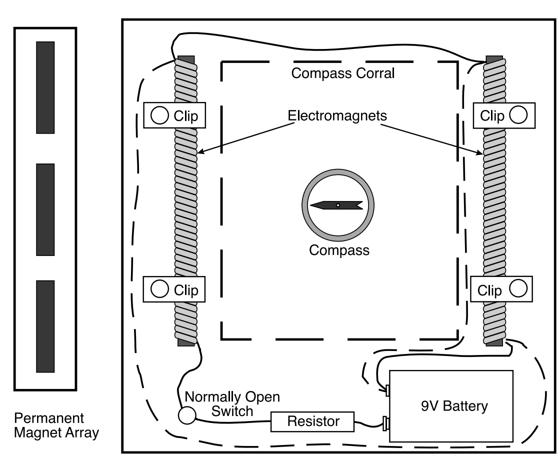

Figure 5. Top view of a schematic of the electrical connections. The dashed lines are used for electromagnets that are both wound in the same direction. The dashed square is called the “compass corral” and is the region used for the demonstration.

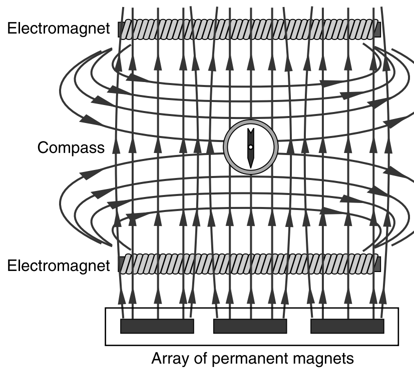

Figure 6. Top view of some magnetic field lines from the electromagnets and the permanent magnets. Note that the field lines generated by the array of permanent magnets are almost straight and parallel. This results in a gradient of field strength that decreases as the distance from the magnets increases, while the field is laterally uniform. When pulsed, the electromagnets generate a field that is perpendicular to the field lines of the permanent magnets within the compass corral.

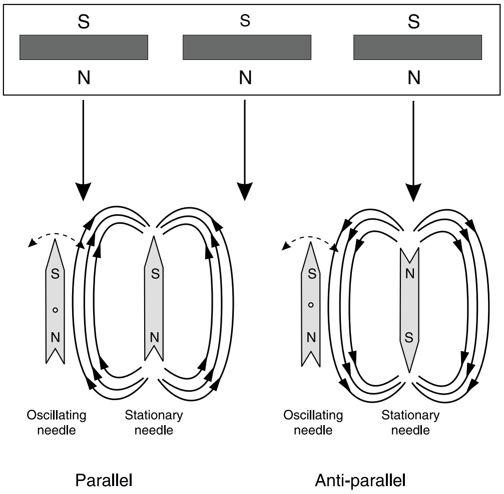

Figure 7. When a stationary needle is aligned parallel to the oscillating needle (left part of the figure), the field from the stationary needle opposes the field from the permanent magnets, reducing the oscillation frequency. Conversely, when the stationary needle is aligned antiparallel to the oscillating needle (right part of the figure), the field from the stationary needle is in the same direction as the field from the permanent magnets, resulting in an increased oscillation frequency.

worthy that for identical compasses the same distance from the array of permanent magnets (i.e., at the same field strength), the natural oscillation frequency of the compass needle in the pulsed demonstration matches the resonance frequency of the compass needle observed using the aforementioned continuously oscillating magnetic field of the magnetic stir plate.

Three- or Five-Compass Demonstration

Another way to demonstrate the relationship between the oscillation frequency and magnetic field strength is to arrange three or five compasses in the dot patterns used on dice. When the pulse is applied, the compass needles will be oscillating at different frequencies, with the highest frequency nearest the permanent magnets. The three-compass arrangement provides a convenient introduction to the MRI demonstration described below.

Demonstration of Shielding

Electronic shielding can be demonstrated by placing a ring constructed of thin sheet steel around the compass to represent electron density; see the Supplies section for details regarding the ring. Pulse the electromagnet to initiate the compass needle oscillation and observe its frequency. Placing the metal ring around the compass will reduce the magnitude of the magnetic field around an excited compass needle, resulting in a lower frequency of oscillation. This is analogous to the reduction in the field strength around the nucleus in the NMR experiment that results from the presence of electron-donating substituents and leads to a lower resonance frequency. Deshielding can be illustrated when the ring is removed from around the compass, causing the frequency of oscillation to increase. This is analogous to the increase in resonance frequency that results from the deshielding effect of electron-withdrawing substituents.

Demonstration of Spin–Spin Coupling

Spin–spin coupling can be demonstrated by observing the change in oscillation frequency of a compass needle in the presence of a stationary compass needle aligned either parallel or antiparallel to the oscillating needle. To illustrate spin–spin coupling, a compass needle is removed from a compass and glued to a thin piece of nonmagnetic material, preferably Plexiglas. The stationary needle is placed in a parallel or antiparallel alignment above a compass whose needle is oscillating and is seen to decrease or increase the oscillation frequency, respectively.

To observe this effect, it is important to note that a compass needle is a bar magnet whose south magnetic pole is the end that points north. When the stationary needle is aligned parallel to the oscillating needle, it exerts a field opposing that of the permanent magnets, resulting in a decrease in the frequency of oscillation (Fig. 7). If the needles are aligned in the antiparallel direction, the stationary needle exerts a field reinforcing that of the permanent magnets and the frequency of oscillation increases (Fig. 7). The magnitude of the change in the frequency will depend on the strength of the interaction between the stationary needle and the oscillating needle. For the most effective demonstration, approach the oscillating needle from above with the stationary needle in the parallel position, remove it, and then approach in the antiparallel position. Adjust the height at which you hold the stationary needle above the compass so that the change in the needle's frequency is visible, but not so close that the field from the stationary needle overwhelms that of the permanent magnet, which may cause the needle to flip or stop oscillating. This dependence on distance can also be used to show that the magnitude of spin–spin coupling depends on distance, as observed in NMR experiments. For example, typical NMR spectra exhibit spin–spin coupling between protons on adjacent carbon atoms, but coupling with more distant nuclei is not generally observed.

Demonstration of Magnetogyric Ratio

Nuclei with different magnetogyric ratios may be modeled by adjusting the mass of a compass needle. Holes are drilled or cut in the cover of the compass, and pieces of opaque, non-magnetic material are glued to each end of the needle. The demonstration is made more effective if the added material extends beyond the edges of the needle so it is visible on an overhead projector. The weights should be added carefully so as to keep the compass needle balanced on its post. The heavier needle will oscillate at a lower frequency, analogous to a nucleus with a smaller magnetogyric ratio (Fig. 1).

Demonstration of Free Induction Decay

The pulse demonstration lends itself to a free induction decay (FID) demonstration. This is the exponential decay of the signal collected from a Fourier transform–NMR (FT–NMR) experiment. After the pulse is applied, the amplitude of the compass needle oscillations will decay exponentially. This may be observed by measuring the amplitude as a function of time.

Demonstration of Magnetic Resonance Imaging (MRI)

MRI is, in essence, spatially resolved NMR. The spatial resolution obtained in MRI depends on the fact that equivalent nuclei have oscillation frequencies that vary with magnetic field strength. In NMR, it is important to maintain a homogeneous magnetic field throughout the sample. In MRI, a gradient of magnetic field strength is applied to the subject along an axis (Fig. 8). The magnetic field gradient is applied by a superconducting magnetic coil that surrounds the patient so that the patient is in essence placed into the center of an electromagnet. This is the origin of the “tunnel” shape of traditional MRI instruments.[11] The large cover for the tunnel houses the cooling system for the superconducting coil.

Equivalent nuclei located in a region of lower field strength oscillate at a lower frequency than nuclei in a region of higher field strength. Thus, the resonant frequency of a nucleus will depend on its location within the subject, since the field strength varies with position. If the signals from the resonating nuclei are separated according to frequency, the number of chemically equivalent nuclei at each location can be determined. In MRI, ^{1}H NMR is used to determine water density and thus tissue structure. For example, tissue with high water content (such as muscle) will have a stronger signal than tissue with lower water content (such as bone). If the direction of the field gradient is rotated and the measurement is taken again, then two sets of spatially resolved data have been collected. This procedure is repeated until a large number of data sets are collected for many field gradient directions. These data are then used to reconstruct the three-dimensional structure of the tissue. Additional details regarding the MRI experiment have been summarized (*5–9*).

To demonstrate these principles the array of three collinear permanent magnets is used to generate a field gradient with parallel field lines (as shown in Fig. 6), analogous to that in the MRI experiment. Recall that compasses within the corral that are equidistant from the permanent magnet array will have nearly the same resonant frequency. This is easily seen

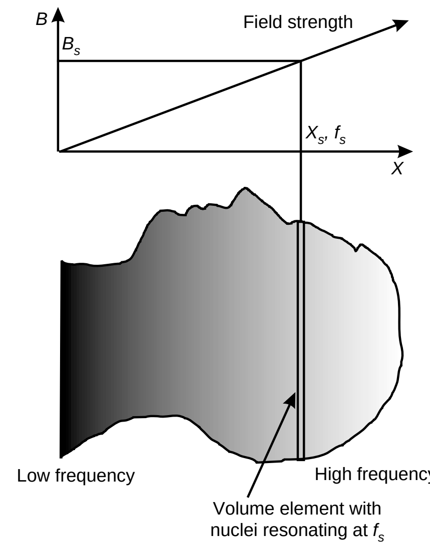

Figure 8. Effects of a magnetic field gradient on a subject. The applied field gradient causes chemically equivalent nuclei to resonate at different frequencies depending on their location within the subject. For the figure shown here, the subject is exposed to a field gradient that is of lower field strength near the neck and at a higher field strength at the top of the head. The nuclei in the neck will thus be resonating at a lower frequency than the nuclei at the top of the head. By isolating the signal from nuclei resonating at a particular frequency (f_s, as shown here), the signal from one volume element (at x_s, as shown here, characterized by field strength B_s) of the subject may be measured.

in the pulsed three- or five-compass demonstrations described earlier. The extension to the MRI experiment may be mimicked by rotating the array of three permanent magnets around the corral with the center of the corral as the center of rotation. One simple setup for this demonstration comprises placing three compasses along a diagonal line through the square, as shown in Figure 9a. When the permanent magnets are positioned along an edge of the square parallel to the electromagnet coils and the electromagnet is pulsed, each compass needle will oscillate at a different resonant frequency. Next, the permanent magnet array is rotated 45°, as shown in Figure 9b, so that it is parallel to and thus equidistant from all three compasses. When the electromagnet is pulsed again, the compass needles will be oscillating at the same frequency.

An alternate way to show the basic principles of MRI is to use the magnetic stir plate setup described earlier (Fig. 3) with two or three compasses arranged on a diagonal (analogous to their arrangement in Fig. 9). The magnetic stir rate is then varied so as to sequentially bring each compass into and then out of resonance. Next, the array of permanent magnets is rotated so that it is parallel to and thus equidistant from both (or all three) compasses, analogous to the rotation shown in Figure 9b. Again, vary the stir rate, but now demonstrate that the compasses come into resonance at the same frequency.

Explanation of the Analogy

An oscillating compass needle provides an excellent analogy to the behavior of magnetic nuclei.[12] Just as a spinning magnetic nucleus will precess about the axis coincident with

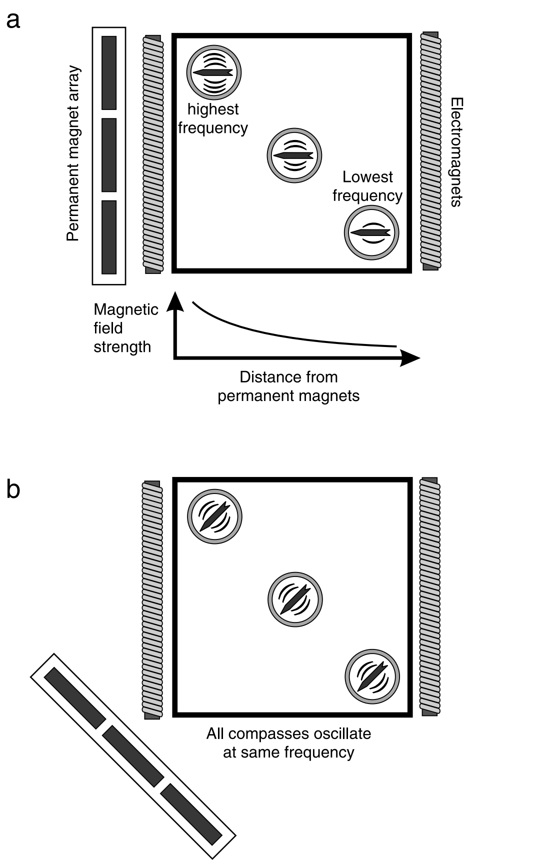

Figure 9. A top view of the arrangement used for the pulsed MRI demonstration. (a) When the array of permanent magnets is aligned parallel to the edge of the compass corral, the compass needle that is closest to the array oscillates with the highest frequency, and the compass needle that is farthest from the array oscillates with the lowest frequency. This variation in frequency is due to the decreasing magnetic field strength as shown in the graph. (b) When the array of permanent magnets is rotated by 45°, the compasses are all equidistant from the array and oscillate at the same frequency.

the applied constant magnetic field (*B*), the compass needle will align itself in the direction of the field applied by permanent magnets. One important difference between a nucleus and the compass needle analogy is that, in the presence of a magnetic field, the nucleus is naturally in a state of precessional motion. In contrast, the compass needle will remain stationary and aligned with the static field until perturbed.

In the continuous wave (CW) NMR experiment, the nuclei are irradiated with a radio frequency (rf) electromagnetic signal that is polarized perpendicular to the constant magnetic field. If the frequency of the rf signal is the same as the frequency of the nuclear precession, resonance results, promoting the nucleus to its excited state. This is an absorption event that can be monitored by measuring the intensity of the rf signal transmitted through the sample. Likewise, in the magnetic stir plate demonstration, when the frequency of the continuously oscillating magnetic field is adjusted to be the same as the natural oscillation frequency of the compass needle, resonance results and the needle's amplitude of oscillation increases. This energy absorption is observed visually.

In the pulse NMR experiment, the nuclei are excited by a rf pulse that is polarized perpendicular to the constant field *B*. This excitation results in a perturbation of the equilibrium condition and causes the precessing magnetic dipole of the nucleus to rotate in a plane perpendicular to the direction of the constant field, with a frequency proportional to the strength of the applied constant magnetic field. In essence, the pulse NMR experiment consists of monitoring the collection of nuclei as they return to equilibrium after this perturbation. In the pulse demonstration, the compass needle is perturbed from its equilibrium position by a magnetic field perpendicular to the constant field of the permanent magnets created by pulsing the electromagnets. This perturbation causes the needle to begin oscillating, and the relationship between the needle's oscillation frequency and the magnetic field strength is readily illustrated, as the oscillation frequency can be seen to depend on the compass's position in the magnetic field.

Despite the simple effectiveness of these demonstrations for visually illustrating some of the principles of NMR spectroscopy, the analogy contains several limitations. In the NMR experiment the resonance occurs between two quantum energy states; in the demonstrations described here there are no quantized states. A magnetic nucleus in the presence of a constant magnetic field precesses about the axis of the field direction when unperturbed; in the demonstrations, however, the compass needle, which is constrained to two-dimensional motion, is at rest until excited. In the NMR experiment, equivalent nuclei (e.g., protons attached to the same carbon atom) do not couple to one another; in the demonstration all compass needles will interact magnetically when in proximity to each other. The roughly exponential decay of the compass needle in the pulse demonstration is due to friction between the needle and the post upon which it rests; in the NMR experiment the free induction decay is primarily due to energetic loss to the "lattice" or surrounding material.

Conclusion

The illustration of resonance frequency and its dependence on magnetic field strength can be easily demonstrated to provide a basis for understanding this fundamental principle of NMR spectroscopy. These demonstrations can be extended to other important aspects of the NMR experiment, such as shielding, spin–spin coupling, magnetogyric ratio, and free induction decay. Illustrating the relationship of the resonance phenomenon to the MRI experiment makes the valuable connection between NMR and a powerful and increasingly common medical diagnostic tool. These demonstrations are inexpensive and relatively simple to construct, and can be used repeatedly.

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The MRSEC Web page at *http://mrsec.wisc.edu/edetc/NMR* presents videos and photos of some of the demonstrations described herein.

Notes

1. Substituting into the Boltzmann equation,

$$\frac{\text{number in upper state}}{\text{number in lower state}} = e^{-\Delta E/kT} = e^{-h\nu/kT}$$

using 60 MHz for ν gives a population ratio of 0.999991. The lower level is only slightly favored, with 9 out about 2 million nuclei available for observation. At 200 MHz the population ratio is 0.999968 and 32 of about 2 million nuclei are available. With a larger magnetic field (and correspondingly larger frequency) sensitivity is higher, owing to the greater population difference.

2. Some overhead projectors generate a magnetic field that may interfere with the demonstration. We recommend making a trial run of the demonstration on the projector to be used.

3. The one-inch diameter Silva “micro 28” compass works best. These are often available in a sports or outdoor supply store or catalogs for about $6.00 each. The micro 28 compass is also available from the Brunton Company, 620 East Monroe Avenue, Riverton, WY 82501; Phone: 307/856-6559; FAX: 307/856-1840; Orders: 800/443-4871; email: *Info@Brunton.com*; Web site: *http://www.brunton.com/recreational_products/intermediate_frameset.htm*. Other compasses will work, but they must be plastic and transparent.

4. *Craft Magnets*: Many fabric stores carry encased ($\frac{1}{2} \times 1 \times 2$ in.) strong magnets. Jo-Ann Fabrics and Crafts Stores carry Super Magnet magnets. These magnets may also be ordered via the World Wide Web at *http://www.blue-feather.com* and are called MagnaMight refrigerator magnets. They cost about $2.50 ea. *Nd–Fe–B Magnets*: Magnet Sales and Manufacturing Co., 11248 Playa Court, Culver City, CA 90230-6100; Phone: 310/391-7213; FAX: 310/390-4357. Magnets prod. #3SNE209620. These Nd–Fe–B magnets cost about $20.00 each.

5. Corning Glass Works, Model P.C. –351, Stirrer Hot Plate.

6. Radio Shack, Part No. 271-132; Digi-Key, Part No. 10W–10-ND.

7. Radio Shack—metal clip, but no connections or lead wires, Part No. 270-326B; Digi-Key—holder with lead wires, Part No. BH9V-W-ND.

8. Radio Shack, Part No. 275-1547.

9. Sixty-eight feet of insulated 24 ga. Cu wire is required and can be purchased at Radio Shack.

10. As the magnetic field oscillation frequency nears the compass needle resonance frequency, the compass needle may be observed to oscillate with alternately large and small amplitudes. This behavior, known as “beating”, is the result of the sum of two periodic functions, the oscillation of the magnetic field from the stir plate and the natural oscillation frequency of the compass needle. At resonance, the needle oscillation amplitude will be large and constant over time.

11. The technology surrounding MRI instrumentation is changing rapidly, and modern instruments use a more sophisticated arrangement of magnetic fields to collect the data in a shorter period of time. Some newer MRI instruments employ pulsed-field gradients that result in different relative phases of the nuclei along a given direction. This simultaneously provides information regarding the tissue disposition along an additional axis, speeding image collection and eliminating the need for rotation of a magnet array (*9*).

12. The compass needle itself can be modeled as a torsional pendulum. The torsional pendulum is the rotational analog to a mass on a spring, which follows Hooke’s law, $F = -kx$. In the case of a torsional pendulum, the displacement (x) is replaced by the angular displacement (θ), the force (F) is replaced by the torque (τ), and the spring constant (k) is replaced by the torsional constant (κ). This results in the equation

$$\tau = -\kappa\theta$$

In this demonstration the force component perpendicular to the compass needle in the plane of the corral will be equal to the total magnetic force (between the compass needle and the permanent magnets) multiplied by sin θ. At small values of θ, $\sin\theta \approx \theta$, and the equation above is valid for small needle deflections. If the system is further evaluated as a frictionless simple harmonic oscillator, then the oscillation frequency obeys the equation

$$\omega = \sqrt{\frac{\kappa}{I}}$$

Here, I is the moment of inertia of the compass needle and ω is the frequency of oscillation. Note that the frequency is dependent on the square root of the torsional constant. Since the torsional constant depends on the force of magnetic attraction between the compass needle and the permanent magnets, which depends (nonlinearly) on the distance from the permanent magnets, the frequency of oscillation will depend on the distance between the compass and the permanent magnets. Note that this equation also describes why the magnetogyric ratio demonstration behaves as it does: by changing the mass of the compass needle, the moment of inertia (I) is changed. Thus, attaching weights to the compass needle increases I, resulting in a decrease in the oscillation frequency. If a more in-depth discussion of the classical mechanical properties of a torsional pendulum is desired, most introductory college physics texts contain a treatment of this system.

Literature Cited

1. Johnson, R.; Bethume, D.; Yannoni, C. *Acc. Chem. Res.* 1992, *25*, 169–175.
2. Landis, C.; Cleveland, T.; Cloninger, M.; Pollock, D. *Buckyballs, Diamond and Graphite*; New Traditions Curriculum Project; University of Wisconsin: Madison, 1995.
3. Chapman, O.; Russell, A. *J. Chem. Educ.* 1992, *69*, 779–782.
4. Parmentier, L.; Lisensky, G.; Spencer, B. *J. Chem. Educ.* 1998, *75*, 470–471.
5. Smith, H.; Ranallo, F. *A Non-Mathematical Approach to Basic MRI*; Medical Physics Publishing: Madison WI, 1989.
6. Valk, J.; MacLean, C.; Algra, P. *Basic Principles of Nuclear Magnetic Resonance*; Elsevier (Biomedical Division): Amsterdam, 1985.
7. Oldendorf, W.; Oldendorf, W. Jr. *Basics of Magnetic Resonance Imaging*; Martinus Nijhoff: Boston, 1988.
8. Smith, S. *Anal. Chem.* 1985, *57*, 595A.
9. Skoog, D. A.; Holler, F. J.; Nieman, T. A. *Principles of Instrumental Analysis*, 5th ed.; Harcourt Brace: Philadelphia, 1998; pp 486–491.