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The Magnetic Resonance Myth of Radio Waves

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An inaccurate description of magnetic resonance is current among those employing it in medicine and biology. The technique is purported to use radio waves for both stimulation of the sample and for reception of the ensuing signal. Arguments are presented which counter this myth, and using only magnetic fields, an accurate classical description of transmission and reception is given.

INTRODUCTION

A strange notion exists that nuclear magnetic resonance (NMR) uses radio waves for both excitation of a sample and for the reception of signal. Where this idea originated is difficult to say, for it cannot be found in any of the basic, long-established texts. However, its acceptance within, at least, the medical imaging community is now nearly universal, and attempting to combat the weight of several books that contain this error is a depressing matter, for one is often greeted with ill-masked skepticism. Why then should one bother? On the one hand, there is the academic's annoyance at the perpetration of a falsehood, and with it, the instilled belief that a faulty building block can eventually cause the learned tower to tumble. On the other hand, there is the knowledge that the NMR frequency range is sandwiched between those of electric power lines and microwaves, both of which have been accused of being health hazards. Guilt by false association with electric fields thus lurks in the wings.

Part of the problem perhaps lies in trying to use elementary quantum mechanics to explain the NMR phenomenon. The picture of two levels separated by energy $h\nu_0$(where h is Planck's constant and ν_0 is the Larmor frequency) is appealing in its simplicity: Transmission involves the absorption of photons which cause transitions from the low energy state to the high energy state (see Figure 1). Of course, photons are usually portrayed in undergraduate texts as quanta of light, which is simply electromagnetic radiation, but with NMR the frequency of "radiation" is much lower, so the photon must be a radiowave! Conversely, after transmission, relaxation occurs as nuclei drop back into the lower energy state. In the process, they emit photons (radio waves again), and an antenna picks up the signal and passes it to the radio receiver that is the NMR system. The whole scenario is attractive: It appeals to the familiar in its use of radio waves and carries authority with its invocation of quantum mechanics. Unfortunately, it is also erroneous and misleading.

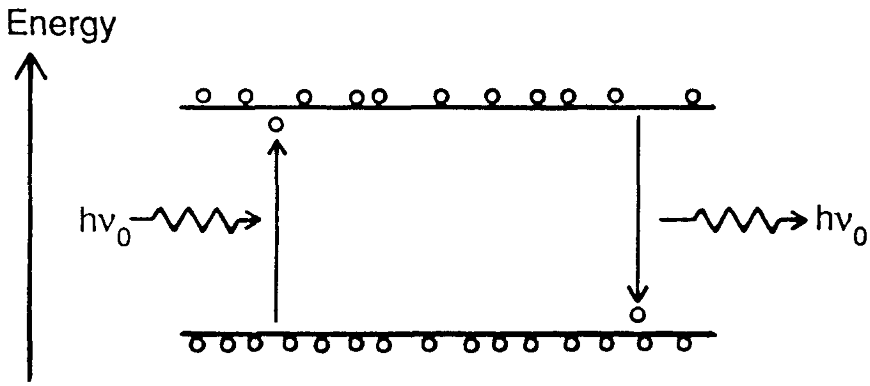

Figure 1. A simplistic quantum mechanical description of magnetic resonance which only describes energy states, and says nothing concerning coherent and induced transitions. Energy is absorbed as the population of the higher level increases at the expense of the population of the lower level. Energy is released by the reverse process. However, the release is stimulated by the Brownian motion of adjacent atoms, and energy passes as a minute amount of heat to the surroundings (longitudinal relaxation), not out of the system as radio waves.

To describe the basic NMR experiment in accurate quantum mechanical terms is extremely difficult, and were it necessary, there would be good reason for employing a simplification, along the (albeit totally inadequate) lines of Figure 1. However, one of the rocks upon which the discipline of quantum mechanics is built is the Correspondence Principle. Briefly put, this Principle states that when there is a large number of individual, unconnected or uncoupled players on the scene, any quantum mechanical phenomenological description must merge and agree with a classical description, for both are accurate representations of the same phenomenon. Now in 1 μl of water, there are over 10^{20} very weakly coupled hydrogen atoms, and so classical mechanics can provide an excellent description of, for example, NMR imaging, and fortunately we do not therefore need to use the (in this instance) very difficult quantum discipline. In other words, a simple hydrogen NMR experiment is susceptible to analysis with all the normal paraphernalia of electrical research, and we should be able to discover easily and with confidence what makes it work without resort to quantum theory. We shall see that it involves no more than two magnetic fields -- one static and one rotating -- and that signal reception is by the phenomenon of induction (as in free *induction* decay); something Michael Faraday would have understood in 1831, long before Hertz discovered radio waves.

TRANSMISSION

Picture a skilled electrical engineer who has never heard of NMR being presented for the first time with a magnet, a sample of water, and a set of coils or probes which, together with a radio frequency transmitter and a receiver, generate a signal. Clearly, the signal is magnetic in origin, for the experiment does not work if the magnet is turned off, and it also originates in the water, for with no water there is no signal. However, how is the water stimulated to produce a signal? The engineer knows full well that the term "radio frequency" only means "in a frequency range that could be used, if we so desired, to transmit radio waves," and so he considers three possibilities -- sample stimulation by a radio frequency electric field, by a radio frequency magnetic field or by both, for example (though not necessarily) by radio waves. To determine which phenomenon excites the water, the engineer must design circuits that produce uniquely, at the Larmor resonant frequency, oscillating electric or magnetic fields. He must then test their effects on the water, and so we proceed by considering the design of a circuit which produces only an alternating magnetic field.

This approach commonly generates objections among physicists. Do not Maxwell's Equations -- the fundamental classical equations that govern electrical phenomena -- state quite categorically that whenever there is an alternating magnetic field there is also an alternating electric field, and thus both types of fields and hence a radio wave must be present? The physicists are quite correct; however, the important word in their statement is "whenever". It is not, as we shall see, "wherever".

In the design process, let us first look at the functioning of a dipole antenna used for transmission and reception of radio waves, as shown in Figure 2a.

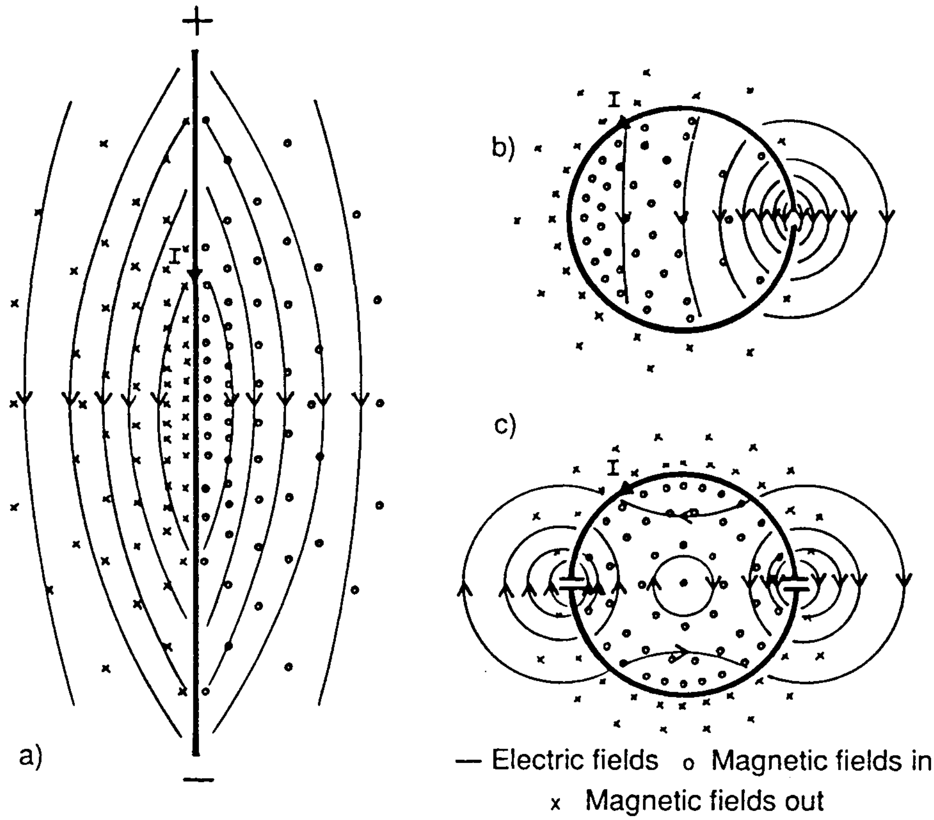

Figure 2. In (a), the fields close to a resonant, half-wave dipole are shown. In addition to these near fields, the dipole is an efficient producer of radio waves, and the latter are the dominant fields at distances greater than a few wavelengths from the antenna. In (b), the dipole has been bent into a loop. Its resonant frequency is barely changed by this action, but its efficiency as an antenna (a producer or receiver of radio waves) is considerably lessened. Note how strong the near electric field is at the gap. In (c), a second gap has been made opposite the first and capacitors added to maintain the resonant frequency. The electric fields from the two gaps cancel at the center of the coil, and the electric field due to the changing magnetic field is also zero there. However, one receives a strong NMR signal from a sample placed in the center, proving that the phenomenon is due solely to magnetic fields, not radio waves.

In the figure, we show the alternating voltage and current on an antenna half a wavelength long. The transmitter supplying the power is not shown. The wire is resonant, in the manner of a guitar string. Close to the wire's center, there is considerable movement of electric charge (i.e., current) back and forth, and hence a strong associated magnetic field. However, at the ends of the wire there is nowhere for the charge to go, and so it backs up, creating a considerable voltage, and hence electric fields approximately as shown. The fields in the proximity of the wire are known prosaically as near fields, and so, close to the antenna we are in the near-field region. Here, the ratio (E/H) of the strengths of the two fields depends on the diameter of the wire and where along the wire we observe, and as this ratio is therefore not fixed, in the near-field region the two fields are said to be **uncoupled**. However, as we move away from the wire, the fields diminish rapidly, and once we are several wavelengths away, we experience both electric and magnetic fields simultaneously in a distinct relationship. Further, as we continue our departure, they now decrease in size relatively slowly (only as the inverse of distance) and they are coupled -- they always bear a ratio of $E/H = 120\pi$ and are perpendicular to one another. These **coupled far fields** are, of course, radio waves travelling out at the speed of light.

Let us now bend the antenna into a loop, as shown in Figure 2b. The distribution of the fields in the plane of the coil is approximately as shown, and both the electric and magnetic fields are rather inhomogeneous (variable in size with position). Note that at the gap, there is a strong electric field, and indeed Hertz employed just such a **Hertzian loop** to detect radio waves -- he saw a spark at the gap caused by the strong near fields induced in the resonant structure by the radio waves. Now let us put a second gap in the loop, directly opposite the first. (We will also add equal capacitances at the gaps to keep the resonant frequency the same.) The resulting fields are shown in Figure 2c, and the important point to note is that at *the center of the loop, there is no electric field.* Note that Maxwell's equations have not been violated. The solution of the second order differential equation curl $\mathbf{E} = -\partial \mathbf{B}/\partial t$ depends on the boundary conditions as well as the rate of change of **B**, and the symmetry of the electrical construction ensures that there is no electric field at the center. The non-conservative electric fields at small radii represent the straightforward solution of the differential equation neglecting the presence of the wire.

Can there be any doubt that placing a water sample in the middle of the coil produces a strong NMR response? If there were, everyone using distributed-capacitance surface coils would be in serious trouble! The experiment shows quite clearly that an alternating near magnetic field at the Larmor frequency stimulates the NMR system, and it is this field that probe designers aim to produce, in distinction to the antenna designer who aims to produce electromagnetic, far field radiation. It follows that NMR probes should not be called antennae! An extension of the experiment, using two orthogonal coils (*1*), shows equally clearly that it is a rotating component of the alternating magnetic field that stimulates the sample. Note that the experiment does not say that radio waves *cannot* be used. After all, they do have an alternating magnetic component. However, the discussion here shows clearly that an antenna *many meters from the sample,* and a transmitter of extraordinary power would be required. Incidentally, an experiment with a pure alternating *electric* field fails.

RECEPTION

So far, our engineer has determined that whatever is happening in the sample of water is stimulated by an alternating or rotating magnetic field. However, how is signal received? A simple experiment suffices to show that radio waves are not responsible. The same type of coil that was used for transmission is now used for reception. However, the receiving coil is progressively moved further and further away from the sample as the latter is repeatedly stimulated with the aid of the transmitter coil. We find that the NMR signal diminishes rapidly, eventually decreasing as the cube of the separation between sample and coil. Such dependence is the hallmark of near fields, for we have seen that radio waves diminish in size only as the inverse of distance. After a careful determination of the signal strength versus separation, another measurement by the engineer reveals an interesting fact. If he uses the receiving coil temporarily as a transmitter (as is often done in practice), and also measures the alternating magnetic field strength *at the sample* as a function of separation, he finds that the two measurements have the same dependency -- the two graphs, one of signal strength versus separation, and the other of field versus separation, look identical. In other words, there is a direct correspondence between the strength of the received signal and the strength, *at the sample*, of the near magnetic field that the receiving coil *would* produce *if* unit current at the Larmor frequency were passed through it.

As soon as the engineer has established this "Principle of Reciprocity" between hypothetical near magnetic field and signal strength, he knows that signal is received by induction. In other words, it is a changing magnetic field in the vicinity of our coil which induces a voltage therein that is passed to the receiver. In our case, the probe is a specially designed surface coil. However, more mundane examples of the same phenomenon include the alternator on a car and the generator at a power plant, both of which use Faraday's Law of induction, and neither of which requires radio waves to describe how *they* work!

The engineer can go further. Just as he showed with two transmitting coils that a rotating near magnetic field was responsible for stimulation of the sample, he can also show with two perpendicular receiving coils that a rotating near magnetic field is responsible for signal reception, and he therefore concludes that as the sample as a whole is not rotating, there are many tiny magnets within, all rotating in unison. Of course, as soon as he tries to consider one of these magnets (an atomic nucleus) individually, he has to study quantum mechanics. However, to venture just a little into that discipline, it is worth noting that in NMR, the probability of spontaneous emission of a photon by a transition between energy levels is "a negligible phenomenon. The description of induced emission, or absorption (in contrast with spontaneous emission) does not require a quantum mechanical description...," Abragam(*2*).

CONCLUSION

The engineer's understanding of NMR is now quite good. We have seen that a few simple experiments are quite sufficient to establish that radio waves are not involved in magnetic resonance. The phenomenon is entirely a magnetic one, and reasonably simple at that. A rotating magnetic field causes the nuclear magnets to rotate (precess). That precession can then be detected by the voltage the **freely** precessing magnets **induce** in the receiving coil. Taking transverse relaxation into account, we observe a **free induction decay**. Classical mechanics can even make a reasonable stab at describing transverse and longitudinal relaxation. Finally, only when we observe phenomena concerning pairs, trios, quartets, etc. of nuclei must we invoke quantum mechanics, for the Correspondence Principle is no longer applicable.

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